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TRANSIENT THERMAL MODELING WITH SIMULATED SOLAR RADIATION

By

B. T. CHAO and M. N. HUANG

RESEARCH ON
TRANSIENT THERMAL MODELING
OF SPACECRAFTS

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Final Report

to

Jet Propulsion Laboratory
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Contract No. 951660

University of Illinois at Urbana-Champaign
Urbana, Illinois 61801

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1. INTRODUCTION AND MAIN OBJECTIVE OF CONTRACT

The possible prediction of the thermal performance of spacecrafts by testing scaled-down models has attracted the attention of many investigators in recent years. The impetus came and still is coming from the continuing demand of building larger and larger spacecrafts, the difficulties associated with the accurate prediction of their thermal behavior by purely analytical means and the high cost of fabricating and testing full-scale prototype hardware. When properly simplified, scale-down models could also serve as a valuable tool in the thermal design of spacecrafts. A review of the status of the art and a discussion of the problems involved in thermal modeling can be found in two survey articles by Vickers [1]* and by Jones [2].

Experimental research on thermal modeling of spacecrafts was initiated at the University of Illinois at Urbana-Champaign in September, 1965 under a NASA Grant, NGR 14-005-048, although theoretical studies were made by the senior author prior to that time. A status report and a final technical report were issued and submitted to NASA. The following are the highlights of the two reports:

(a) <u>Status Report for NGR 14-005-048</u> (March, 1966)

This document presents a brief account of the procurement of a small space simulation chamber and the associated instrumentation and data recording facility. It also reports on the results of a computer study of the heat flow behavior in homogeneous and composite plates with radiative surface condition. It is of significance to note that, even at the early stage of the research, the

*Numbers in brackets refer to entries in REFERENCES.

practical necessity of employing imperfect models was indicated. An excerpt of that report reads:

> "While the theoretical requirements and the basic modeling criteria have been extensively studied and reasonably well understood, the practical implementation of satisfying the criteria must be considerably advanced from what is known today. It is our belief that the success or failure of the modeling technique depends, to a large extent, on one's ability to recognize and distinguish the significant variables from the unimportant ones, to introduce valid simplifications and, if feasible, to establish error bounds whenever approximations are introduced."

The above statements are valid today as they were then.

(b) Final Technical Report for NGR 14-005-048

"Transient Thermal Behavior of Simple Structures in a Simulated Space Environment by Model Testing," by B. T. Chao, J. S. DePaiva and M. N. Huang, University of Illinois at Urbana-Champaign, ME-TR-NGR-048 (July, 1967)

This 78 page report summarizes all relevant experimental results obtained under the Grant which expired in March, 1967. The main objective of the experimental program was to investigate the feasibility of artificially modifying the thermal conductance of metal plates or sheets by electroplating in order to satisfy the transient modeling requirements of systems involving more than one material. A simple geometric configuration was selected for study; it consisted of two rectangular plates of different materials, fastened together to form a lap joint with a flat strip of electric resistance heater sandwiched in between. A prototype, a one-half scale and a one-quarter scale model were fabricated and tested for both steady and transient heat flow condition. The results were generally satisfactory. In no instance, were the predicted temperatures by the one-half scale model more than 16°R in error which was the maximum observed among the steady state results. The average error was less than half of the maximum. The predictions from the one-fourth scale model were better; they showed a maximum error of about 11°R with the average around 5°R. Large errors existed in regions where the heat flow had a significant component normal to the surface. It was emphasized that proper thermocouple installation procedure should be strictly observed.

One appendix of the report contains detailed descriptions of the experimental apparatus, test procedure, specimen preparation and results of measurement of the thermal conductivity of metal plates and sheets used in the investigation as well as that of the electro-deposited copper. Another is concerned with the computation of the specific heat of metallic alloys using the Neumann-Kopp formula. This information should be useful to all who are engaged in thermal modeling research.

The original proposal, which was submitted to NASA in late 1964 and which eventually led to the award of the Grant, outlined a two-year research program. However, financial support was granted for only one year due to limitations of the available fund at that time. Subsequent support of the research was obtained from Jet Propulsion Laboratory of Pasadena, California through Contract No. 951660. The aim of the contract was to determine whether the basic premise laid out in an article by the principal investigator [3] of controlling thermal conductivity can be developed for transient scale modeling. Specifically, the experimental verification of the proposed concept should include solar simulation. As it will soon become apparent, the goal set forth in the contract was more than being fulfilled at the conclusion of the project.

2. SUMMARY OF RESEARCH ACCOMPLISHMENTS PREVIOUSLY REPORTED

The heat flow path in the simple structural system described in the final report to NASA was essentially one-dimensional and there was little radiative interaction between its surfaces. The seemingly oversimplified configuration was selected for the explicit purpose of facilitating the identification of error source and thus pointing to the direction of possible improvement in the experimental procedure. This was found indeed to be the case. The generally improved accuracy obtained in later tests must, at least in part, be attributed to the experience gained during this early phase of the research program in thermocouple installation, instrumentation, chamber operation, etc.

The continuing support from JPL made possible the extension of the experimentation to two additional configurations--one in which strong radiative exchange existed among the surfaces and another in which the heat flow was highly two-dimensional due to the several slots cut in the plates. The results of these two series of tests were summarized in the following technical reports submitted to JPL.

(a) "Results of Transient Thermal Modeling of Simple Structures in a Simulated Space Environment," by B. T. Chao, J. S. De Paiva and M. N. Huang, University of Illinois at Urbana-Champaign, ME-TR-JPL-951660-1 (November, 1967)

(b) "Reproducibility of Temperature Measurements from Model Testing," by B. T. Chao, J. S. DePaiva and M. N. Huang, University of Illinois at Urbana-Champaign, ME-TR-JPL-951660-1 Supplement (January, 1968)

The main conclusion was that, for two-dimensional systems involving two or more materials, the technique of artificially modifying the effective conductivity of metal plates by electrodeposition together with thickness distortion for meeting the transient modeling requirements is feasible and yields satisfactory results. The *average* temperature prediction error was within ±5°R for the simple systems studied, using either the one-half or one-fourth scale models. The reprodicibility of the test data was generally very good. It was emphasized that the radiation property of all model surfaces, participating in radiant exchange with the surrounding or among the surfaces themselves, must be held within close limits *identical* to that of the corresponding surfaces of the prototype.

At the end of the report, it was again suggested that, when complicated structures like those of real spacecrafts are to be studied, "perfect" modeling is impractical and effort should be directed toward developing a rational correction procedure for test data obtained with imperfect models.

3. EXPERIMENTATION WITH SOLAR SIMULATION

All test results reported prior to this date were obtained without solar simulation; electrical heating was the only source of heat. To meet the contract requirement, a relatively inexpensive but rather primitive carbon arc solar radiation simulator was procured from GENARCO, Inc. of Flushing, New York. A 12-inch diameter synthetic fused silica window was designed, fabricated and installed on the existing space simulation chamber.* Since the modeling requirement calls

*The Aluminum Company of America kindly donated the material used for a flange holding the fused silica window.

for a collimated beam of uniform intensity*, a systematic study was made for ascertaining the effect of such variables as operating voltage and current, electrode feeding rate, arc configuration, focal plane location of the optical system, iris opening, the presence of intensity reducing screens, etc., on the stability, uniformity and collimation of the emerging beam. The following section gives a brief account of our findings.

3.1 Performance of GENARCO ME4 Carbon Arc Solar Simulator

The simulator consists of (a) a radiation source produced by carbon arc inside a lamphouse, (b) an optical system and (c) a rectifier supplying the dc current to the carbon electrodes. The actual source of radiation is the crater of the positive carbon electrode and the plasma immediately in front of it. It has an effective diameter of approximately one-half inch. A small electric motor feeds both electrodes and continuously rotates the positive carbon. The 12-phase selenium rectifier has five ac line input terminals and six dc output adjustments for providing the desired voltage and current to the electrodes. The optics of the system is primitively simple; it is comprised of a single, 12-inch diameter fused quartz lens with a focal length of approximately 14 inches. The location of its focal plane is adjustable relative to that of the crater. At the front of the quartz lens, there is an iris diaphragm which can be adjusted to

*Theoretically, this requirement could be relaxed. The modeling criterion would still be met if the prototype and the model are irradiated with beams having spacially *similar* distribution but not necessarily uniform. However, such consideration was ruled impractical.

provide an opening of any size ranging from one inch to twelve inches in diameter. It was found that with a suitable setting of the focal plane position a reasonably well collimated beam could be obtained. When the iris diaphragm is either wide open or so adjusted that it lets through a collimated beam of approximately twelve inches in diameter, the intensity has been found to be highly non-uniform. The uniformity can be improved by decreasing the iris opening and, thus, only at the expense of reducing the useful cross-sectional area of the beam. If a two percent uniformity of beam intensity is desired, the useful diameter of the beam reduces to only approximately five inches for a collimated beam. This diameter is somewhat larger for a diverging beam and smaller for a converging beam*. Because of this handicap, a change in the test plan was necessary. The previously used one-half scale model was taken as the 'new' prototype and the original one-fourth scale model became its one-half scale model.

The distribution of radiation intensity across the beam was determined with an Eppley Mark III radiometer by monitoring the local *total* radiation. The beam divergence was assessed from its aperture wheel readings. With the source emission maintained as steady as possible, the aperture was successively reduced in steps of 1°, beginning from the maximum of 15°. Initially, the radiometer output would exhibit little change as the aperture was reduced. However, a stage would soon be reached whereas a further reduction of the aperture would result in a marked decrease of the radiometer

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*Obviously, the findings reported here apply only to the optical system of the GENARCO simulator available in our laboratory.

output, indicating the effect of shadowing. By comparing this critical aperture configuration when the radiometer was centrally located in the beam and when it was off center, the beam divergence could be estimated. Under certain conditions, beam divergence could also be evaluated from the change in size of the irradiated area on a plane target as the latter is located at different distances from the lens. This scheme, however, is not always infallible as we shall later see. The radiometer was mounted on a vertical panel, capable of being adjusted vertically up and down in a rack which, in turn, rested on two parallel aluminum rails fastened to the laboratory floor. This simple arrangement made possible to scan the beam by the radiometer sensing element with its measuring axis maintained parallel to the beam axis.

The GENARCO simulator was provided with wire screens of three different mesh sizes for reducing beam intensity without significantly disturbing the distribution. These screens were not used in the ultimate testing of model performance reported herein.

Figure 1 shows schematically the arrangement used in the study of the *steadiness*, *uniformity* and *collimation* of source beam radiation. The several lens positions for which the beam quality was measured are shown in the lower right portion of that figure. A divergent beam is obtained with lens at position '1'; a collimated beam emerges when the lens is at position '4' and a converging beam at position '5'. Since a steady radiating beam of constant intensity was of prime importance in our modeling studies, attention was immediately directed toward ascertaining the influence of such operating variables as arc voltage

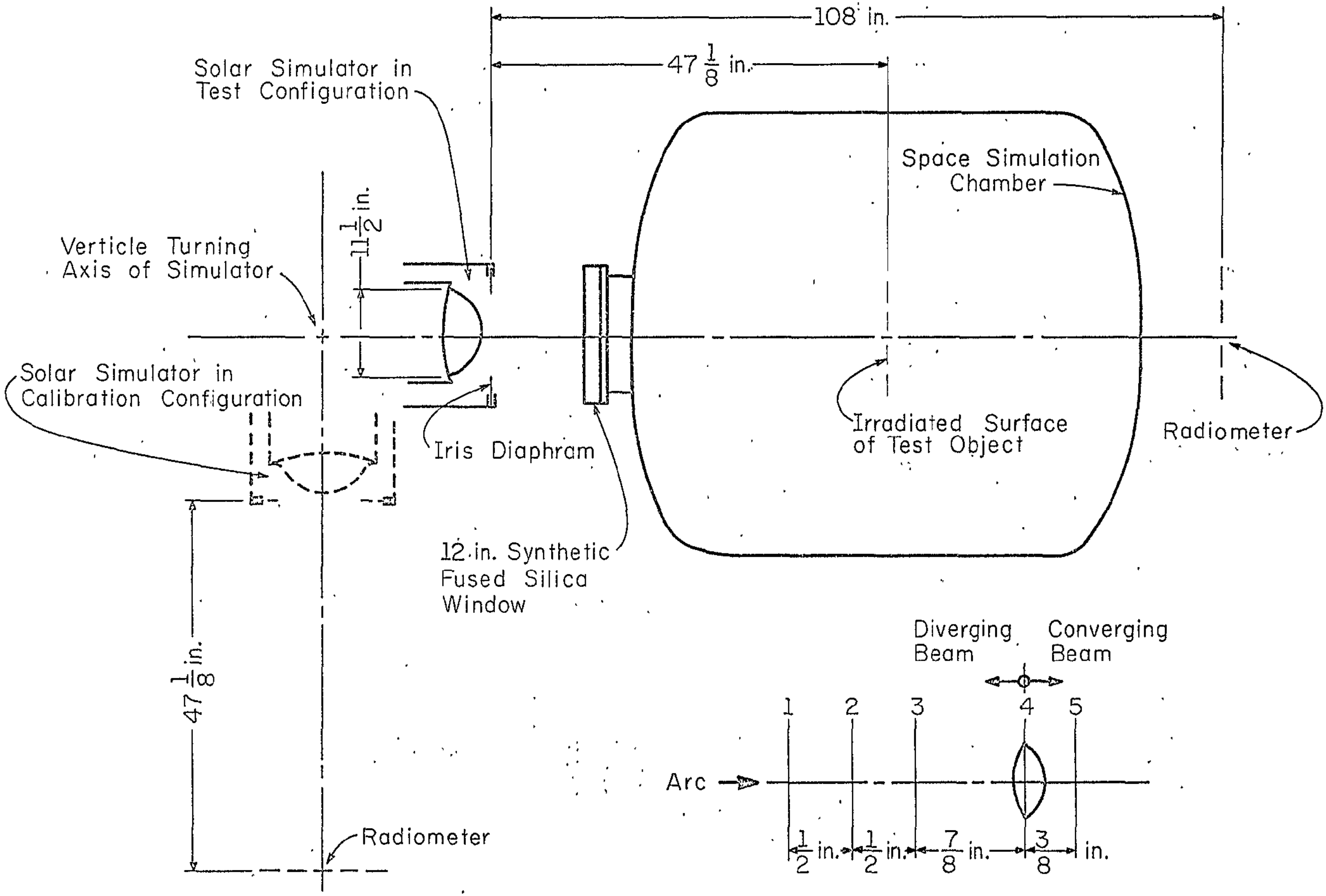

Fig. 1 Experimental Arrangement for Determining Steadiness, Uniformity and Collimation of Source Beam Radiation

and current, arc configuration and the feeding rate of electrodes. Following a systematic search, a suitable combination of these variables was found without difficulty*. These exploratory tests were conducted with the collimated beam passing through the 12-inch synthetic fused silica window of the vacuum chamber. The radiometer was located at approximately 108 inches from the iris diaphragm. This distance has no particular significance; it was chosen mainly for convenience and from the consideration of the available laboratory space. Figure 2 shows a sample record of the radiometer output. The high frequency fluctuations are of no particular significance in the present investigation, only variation in the mean is of our concern. Thus, the long time behavior of the beam radiation from the GENARCO simulator is sufficiently steady over the life span of the positive electrode which is approximately one hour. The radiometer calibration curve is shown in the upper portion of that figure.

At the stated location of the radiometer, the measured intensity distributions of the collimated beam as influenced by the iris opening are shown in Fig. 3. When the iris diaphragm is wide open (14 inches), the intensity distribution is highly non-uniform, exhibiting a peak at the beam axis. It was found necessary to use wire screens to reduce the maximum intensity within the safe operating limit of the Eppley radiometer. A decrease of the iris opening is accompanied by a general

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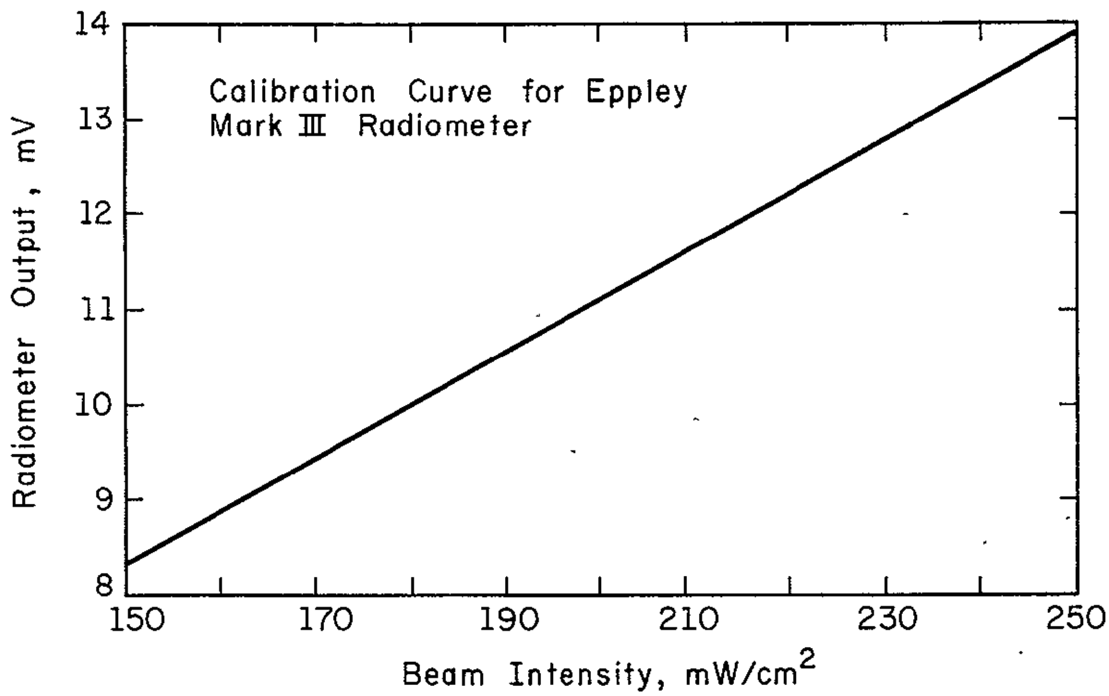
*Satisfactory results had been obtained under the following conditions: ac input at terminal setting 3, dc output at terminal setting 2; electrode feed at speed setting 7.5-8.0; arc voltage ~ 49 v. and arc current ~ 130 a.



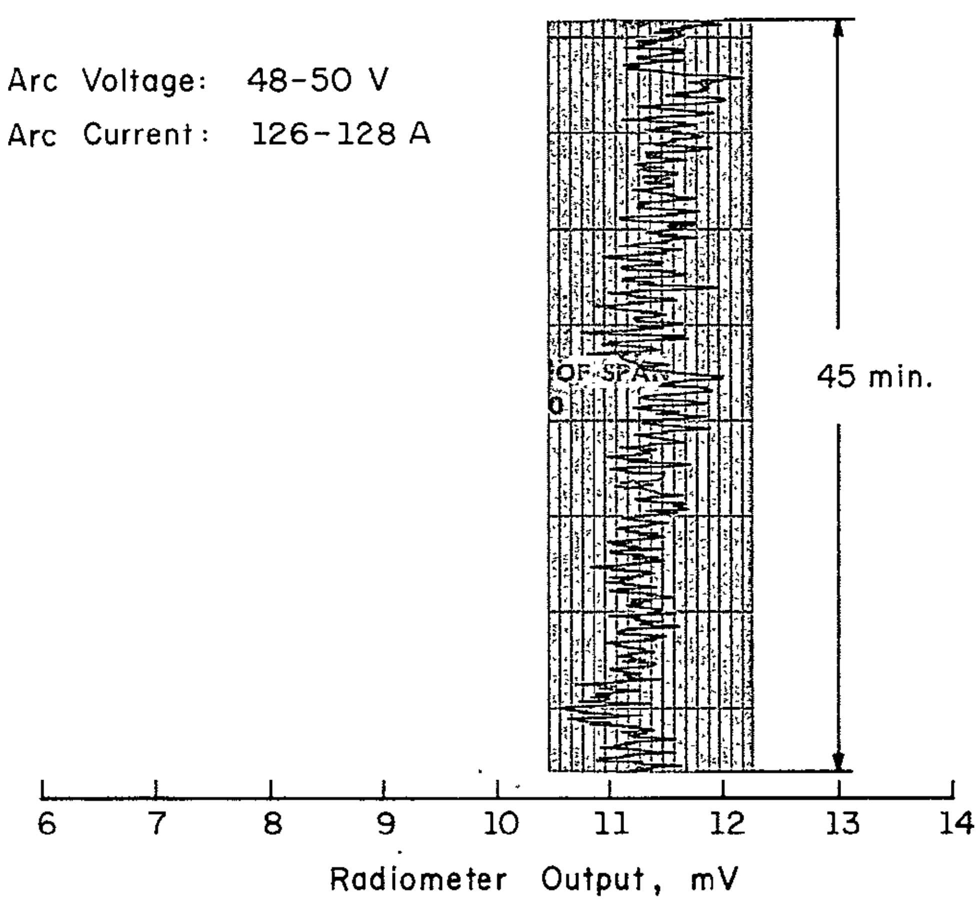


Fig. 2 Fluctuations in Beam Intensity

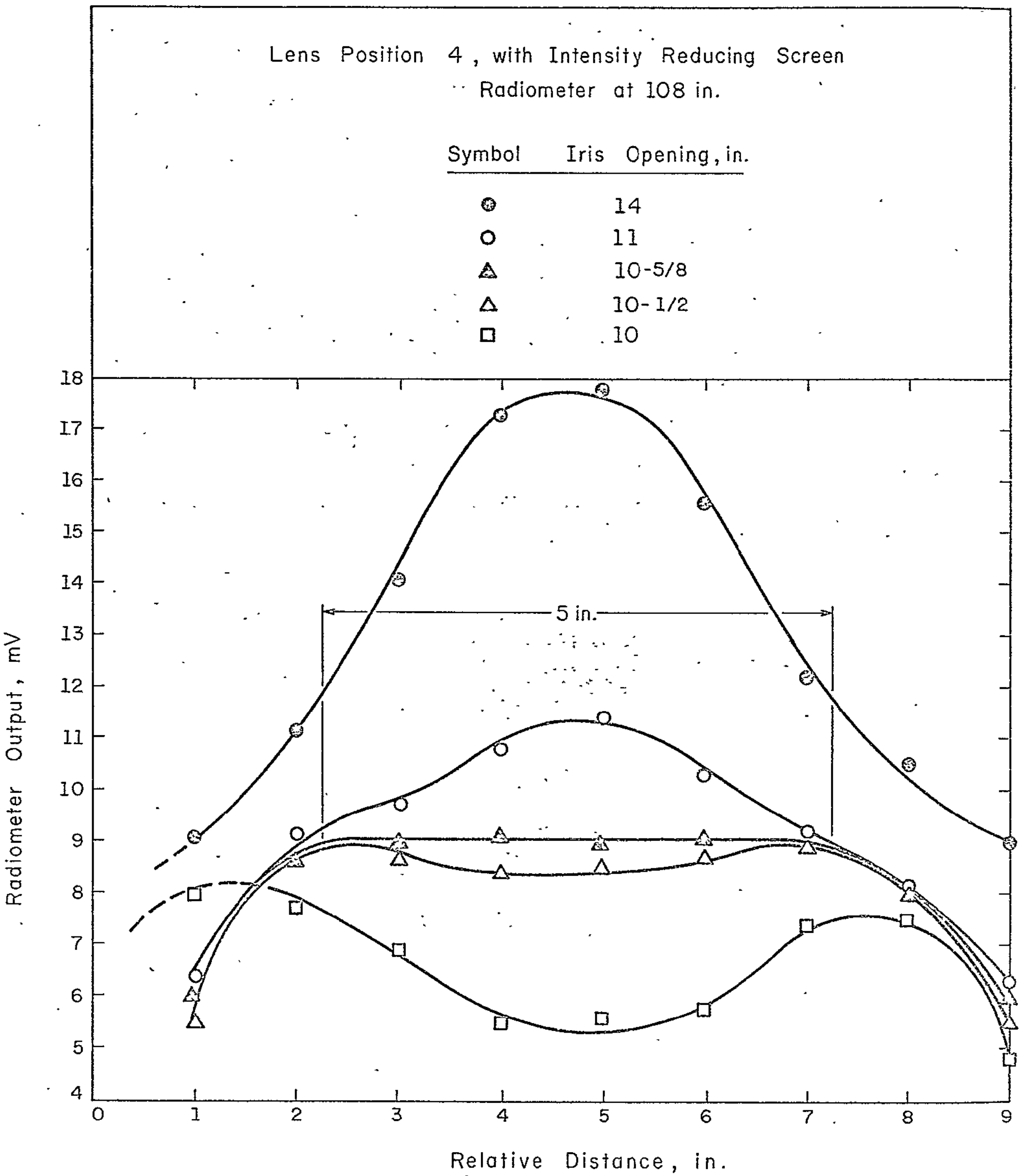


Fig. 3 Intensity Distribution Across a Horizontal Diameter of the Collimated Beam

lowering of the beam intensity, with a proportionately greater reduction in the central core. Further decrease of the iris opening would eventually lead to a reversal in the distribution, namely, a peripheral region of relatively high intensity with a depressed core. These observations indicate that a significant portion of the radiant energy incident on the central core of the target actually emerges from outer periphery of the 12-inch lens. This is the situation for which the beam divergence cannot be determined by noting the change in size of the irradiated area on the target when the latter is moved within certain limited range of distance from the lens.

When the iris opening is set at 10 5/8 inches, the beam exhibits a uniform intensity (within, say, two percent) along a horizontal diameter of approximately five inches. It is also collimated within one degree. Along the vertical diameter of the irradiated area, the intensity exhibits some local undulations although its average remains reasonably uniform.

Similar measurements were made for other lens positions as illustrated in Fig. 1. However, we include here only the results for a divergent beam (lens position '1', half-angle of divergence: 2.4°) and those for the convergent beam (lens position '5'). For the divergent beam, it was found necessary to reduce the iris opening to six inches in order to obtain a centrally flat distribution which, however, extended over a region somewhat larger than that of the collimated beam. Figure 4 shows the measured beam intensity over a target located at a distance 47 1/8 inches from the iris diaphragm. Intensity distributions of the convergent beam for two iris openings are displayed in Fig. 5.

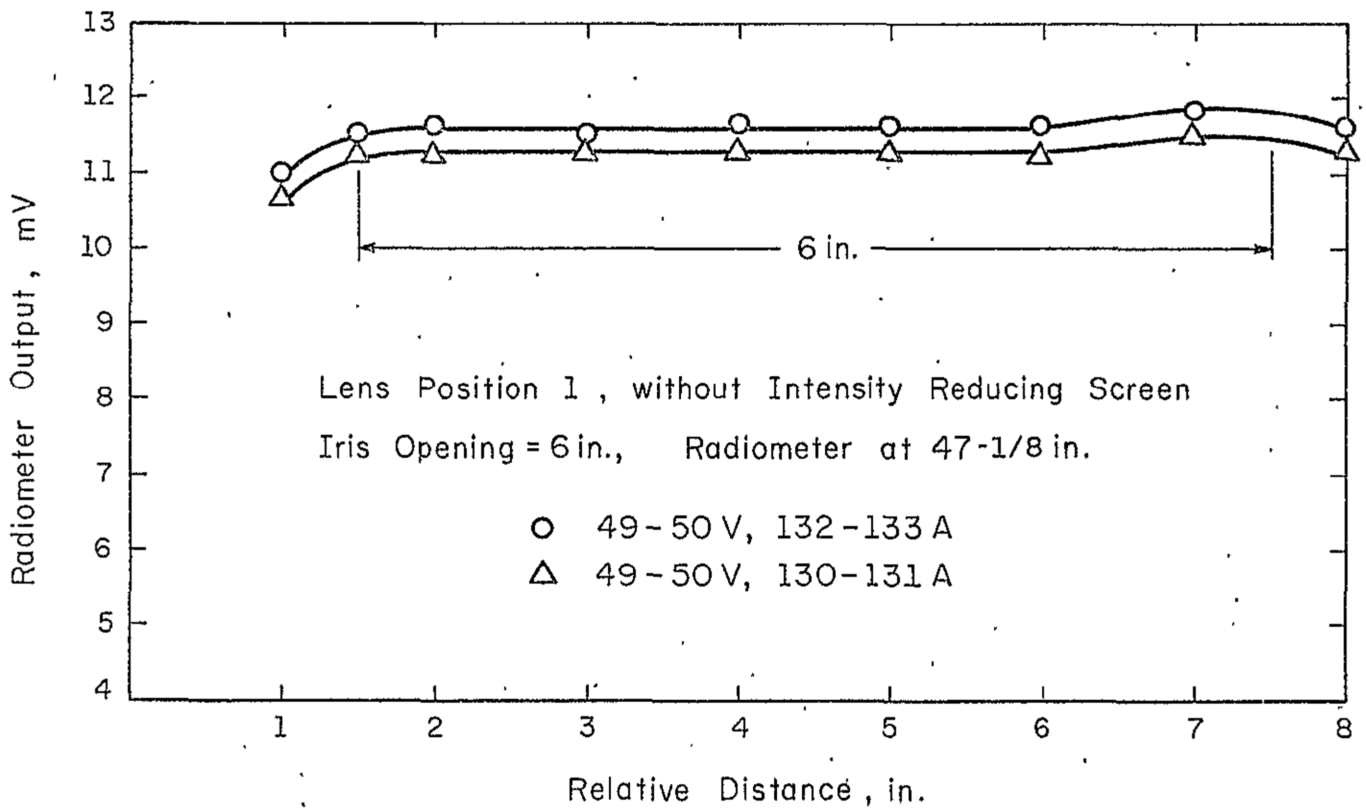


Fig. 4 Intensity Distribution Across a Horizontal Diameter of a Divergent Beam

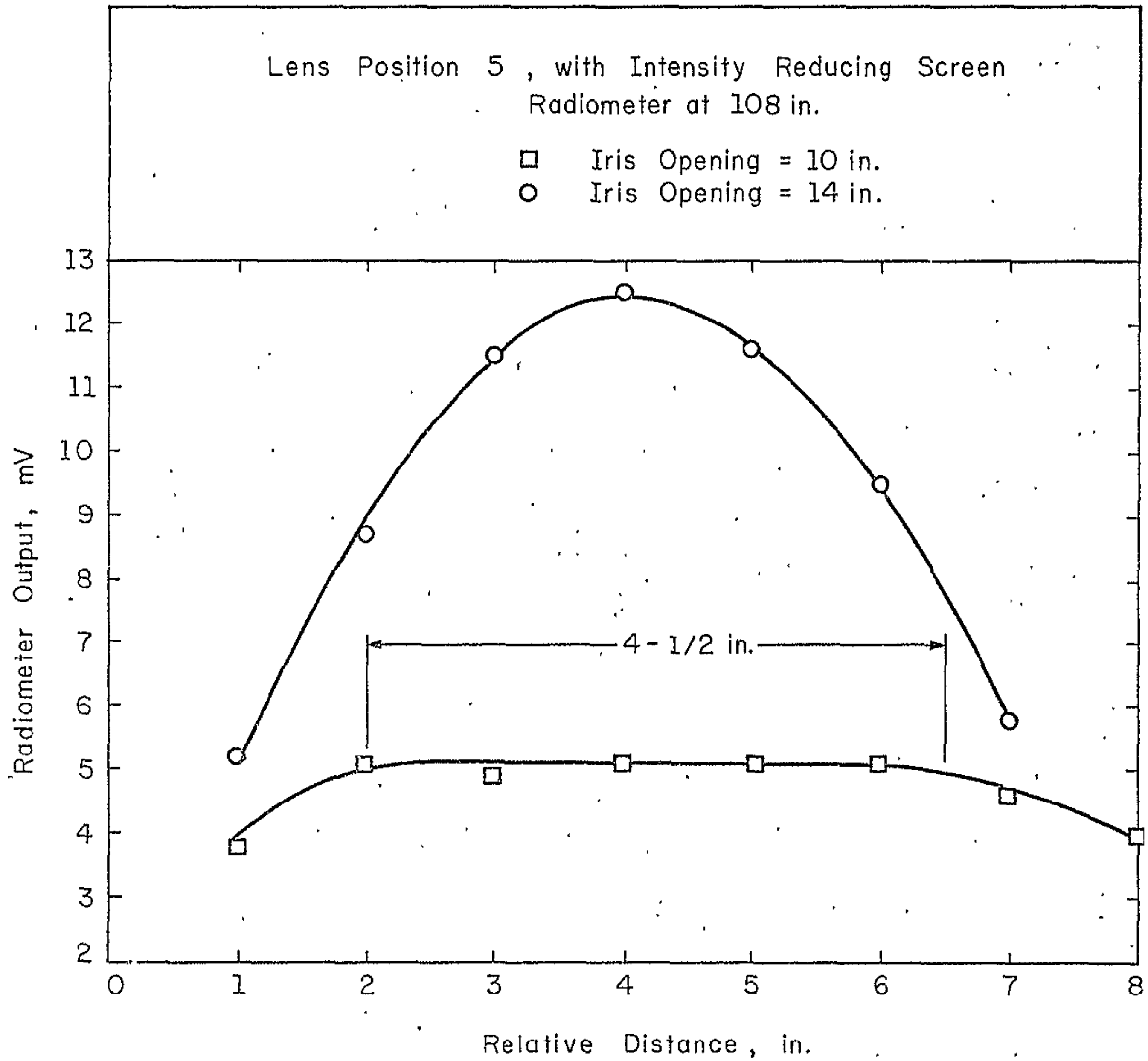


Fig. 5 Intensity Distribution Across a Horizontal Diameter of a Convergent Beam

Upon the completion of the foregoing series of tests, it became clear to us that, with the available optical system, it is not possible to produce a collimated beam of uniform intensity and of a diameter much greater than five inches. On the other hand, if one admits some beam divergence, then a considerably larger target area which remains uniformly irradiated can be achieved by increasing the distance between the simulator and the window of the vacuum chamber. This, however, was not done due to lack of laboratory space. The decision was thus made to conduct this phase of the experimentation using only the one-half scale and one-fourth scale models. The former became the prototype and the latter served as its one-half scale model.

3.2 System Configuration and Surface Coatings

During the first phase of the present study, in which heating was done electrically by resistance heaters, three modeling configurations were investigated. They were referred to as configuration (a), (b) and (c) in the previous reports*. The heat flow paths in configuration (a) and (b) were essentially one-dimensional. By far, configuration (c) had the most complicated temperature field and was thus selected for the present study. For the reader's convenient reference, it is reproduced in Fig. 6. The thermocouple locations and major dimensions of the prototype and of the model are shown. The portion of the surface which was irradiated by the simulator beam is shown cross-hatched. The remainder of the same surface was shaded from the beam

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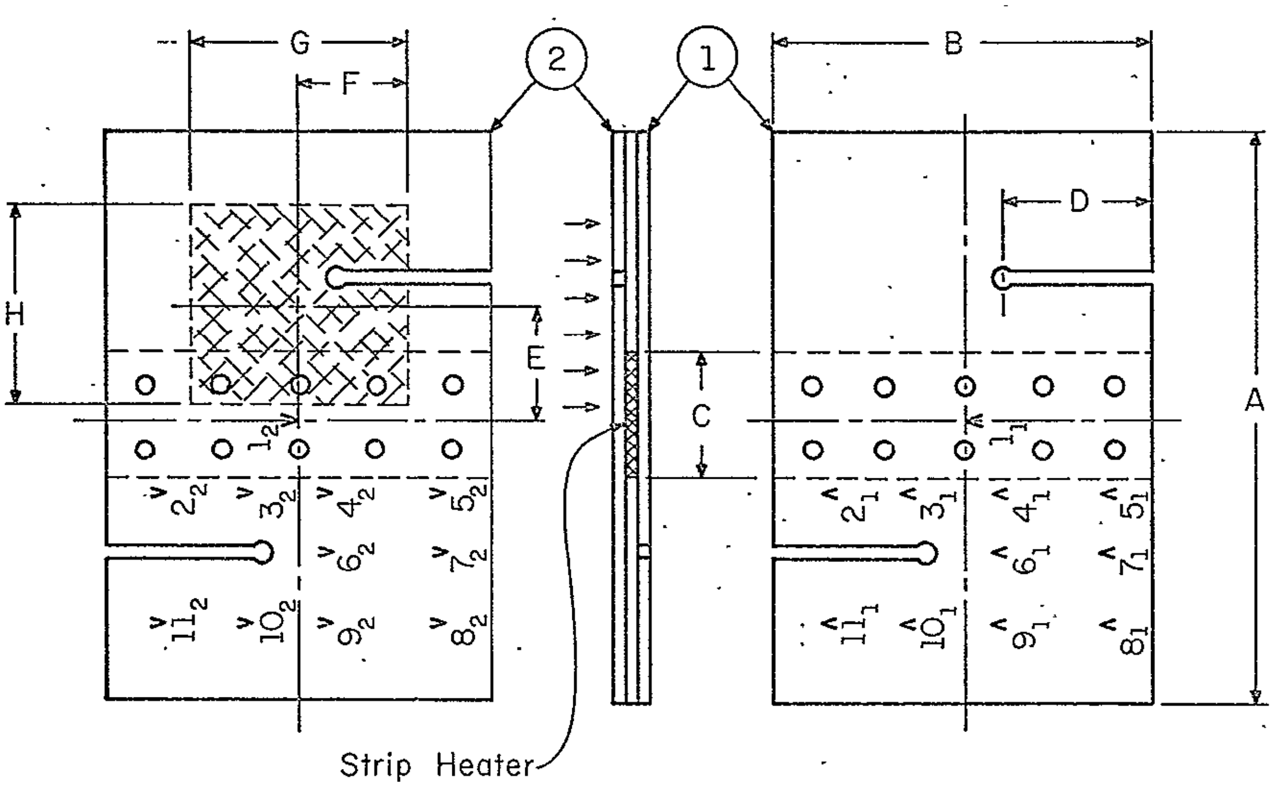
*Final Technical Report to NASA, ME-TR-NGR-048, July, 1967; Technical Reports to JPL, ME-TR-JPL 951660-1, November, 1967 and ME-TR-JPL-951660-1 (Supplement), January, 1968.



		Prototye	1/2-Scale Model
Material	1	5086 Aluminum Magnesium Alloy	Nickel
	2	65-15 Nickel Silver	304 Stainless Steel
Base Metal	A	10	5
	B	7	3.5
	C	2.25	1.125
	D	3	1.5
Irradiated Area	E	2.25	1.125
	F	2	1
	G	4	2
	H	4	2

All Dimensions in inches

Fig. 6 Test Object Configuration

by means of multilayer insulations. In one test series, to be designated as Series A, all surfaces were painted with Cat-A-Lac 463-3-8 black temperature control coating. In another, to be designated as Series B, the surface facing the simulated solar beam was coated with a white paint, PV-100. It is known that this silicon alkyd coating has high infrared emittance but relatively low solar absorptance. This white paint was made available for our use through the courtesy of Mr. William A. Hagemeyer of JPL. It was applied by brushing directly onto the black paint. Application procedure as recommended in a JPL document* was strictly followed.

The electric resistance heaters used in the early experiments were designed according to the model time scale requirement. The resistance to heat flow offered by the mica insulation was not properly scaled. This was permissible since, under the conditions of experimentation existed then, the proper division of the heater power between the two materials, 1 and 2, would not be adversely affected to any significant extent. Such is not the case in the present investigation as only one of the surfaces received energy from the simulated solar beam. Following this observation, the mica insulation of the heater used in the model was redesigned such that its thermal resistance was appropriately scaled. This change introduced some minor disturbance to the heater time scale but was found to be of no serious consequence.

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*"Application of Temperature Control Paints," Jet Propulsion Laboratory Manufacturing Process Specification Document, FS501424, Code Identification NO. 23835, issued June, 1967.

3.3 Test Procedure

A description of the space simulation chamber, the data acquisition and recording system and the general test procedure, including the installation of thermocouples and an analysis of their errors in a space environment, has been given in previous technical reports and, thus, will not be repeated. In all earlier experiments, electric thin strip resistance element was the only heating source. In the present investigation, the simulated solar beam was the sole heating source in one series of tests and the combined heating due to the electric strip heater and the solar beam was used in another test series.

Since the prototype and the model must be similarly oriented with respect to the incident beam radiation, a special fixture was constructed for this purpose. It was fabricated from aluminum rolled sections and rested on the liquid nitrogen cooled shroud at three points. This design was to provide ready accommodation to the crude and uneven surface of the cylindrical shroud. As is shown in Fig. 7, a graduated circular disc, capable of being rotated about a vertical axis, is mounted at the top of the fixture. The disc can also be adjusted up and down relative to the fixture frame. The test object, with the multilayer radiation insulation shield arranged as an integral unit, was suspended from the disc using insulated thermocouple wires of the same gage as that for temperature measurement. In this manner, the test object could be properly oriented* and positioned

*Normal beam incidence was used in all tests reported herein.

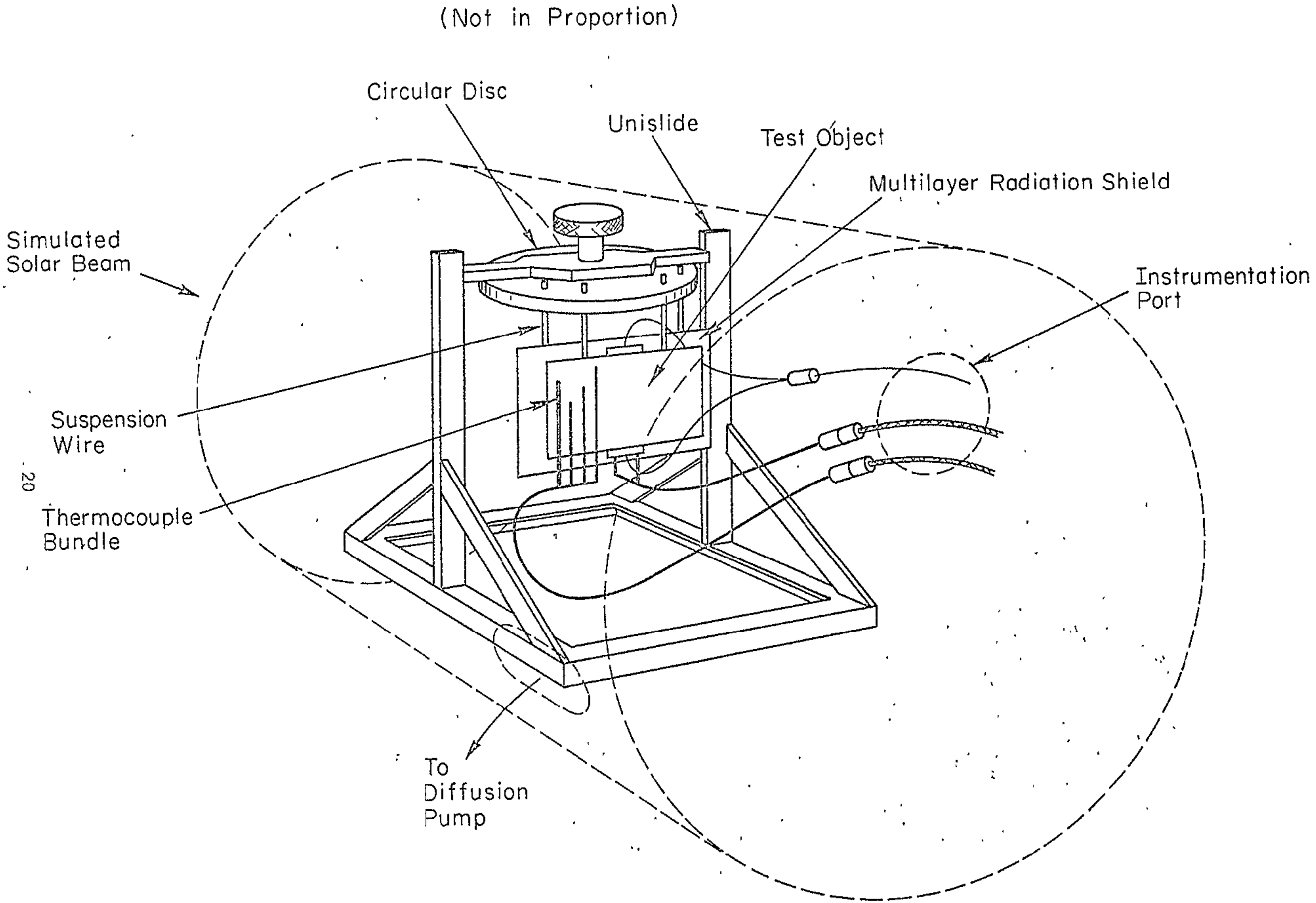

Fig. 7 Fixture for Suspending Test Object in Space Simulation Chamber

relative to the incident beam radiation. Prior to the actual test run, the thermocouples were examined for possible defects in installation by observing their response behavior as the test object temperature was raised and lowered in air by switching on and off the current supplied to the strip heater.

The maximum duration of *continuous* operation of the solar simulator was approximately 60 minutes. The single limiting factor was the length of the negative carbon electrode which could be fed without interruption. The GENARCO simulator has a manually operated douser which protects the condenser lens from the sputtering particles when the arc is struck. It also serves the purpose of letting through or cutting off the beam radiation at any desired instant during the experimentation.

The transient response behavior of the prototype and of the model was studied at two different temperature levels, over different temperature ranges and with two different surface coatings. The initial condition was established by allowing the test object temperature to reduce to approximately 330°R. For the prototype, this would require four and one-half hours of cooling in the vacuum chamber, with liquid nitrogen flowing in the shroud. At this temperature level, the thermocouples exhibited an average rate of cooling of 0.3°F per minute. Table I shows typical measured temperature distribution of the prototvpe and of the model just before the instant when they were subjected to beam radiation. There is no doubt that a more uniform distribution (at a lower temperature level) could be achieved if the test object were allowed to cool for an additional four or five hours

Table I Initial Temperature at 22 Thermocouple Locations

Thermocouple Number	Prototype	One-half Scale Model	Difference
A Material 1			
1_1	328.3	325.7	-2.6
2_1	328.0	327.5	-0.5
3_1	328.0	327.5	-0.5
4_1	328.3	328.0	-0.3
5_1	327.0	328.0	+1.0
6_1	327.5	327.0	-0.5
7_1	325.7	327.0	+1.3
8_1	327.0	326.5	-0.5
9_1	328.3	327.0	+1.3
10_1	327.0	327.0	0
11_1	328.0	327.0	+1.0
B - Material 2			
1_2	332.0	334.7	+2.7
2_2	332.0	334.0	+2.0
3_2	332.5	332.0	-0.5
4_2	332.5	332.5	0
5_2	332.5	332.5	0
6_2	332.5	332.5	0
7_2	332.0	332.0	0
8_2	332.0	331.7	-0.3
9_2	332.0	332.5	+0.5
10_2	333.5	332.0	-1.5
11_2	333.5	332.0	-1.5

All temperatures are in degree Rankine

Prototype Test Run No. 272, Model Test Run No. 472

in the chamber. However, this was not thought justified in view of the expenses involved. It is pertinent to point out that the initial temperature fields can be similar without being steady. If, at every homologous location, the temperature-time plots for the prototype and for the model* are coincident, similar initial conditions would clearly prevail. While the latter is not readily achieved in practice, the error can be kept within limits if the time rate of change of temperature is small.

In the first test run, for which beam radiation was the only heating source, the carbon arc solar simulator was brought up to a state of readiness as the test object was approaching the desired initial condition for the test run. Its arc configuration was checked and maintained as steady as possible. The beam intensity was monitored and recorded. At the desired instant, a designated portion of the test object surface (see Fig. 6) was irradiated by quickly removing the douser in the lamphouse of the simulator. The irradiation lasted 60 minutes for the prototype and 48.78 minutes for the model. All thermocouple outputs were continuously monitored subsequent to the interruption of the irradiation. The simulator was then turned about its vertical axis through approximately 90° until its beam became normally projected onto the Eppley radiometer for checking any possible change in intensity. For all results reported herein, the average intensity of the beam radiation was 205 milliwatt/cm^2 or, approximately 1.46 solar constant. Its variation, before and after each test run either for the prototype or for the model, was less than two percent.

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*In the case of the model, the time involved is the physical time divided by the model time scale which is 0.813.

In the second test run, the test object was first heated by the electric resistance heater for 100 minutes (prototype time) at some suitable power level as shown in Table II. The heating power and time selected are, to some extent, arbitrary. Our objective here is two fold:

(a) to operate the system at a generally higher temperature level, and

(b) to create initially non-uniform temperature fields in the prototype and in the model suitable for subsequent examination of the system's response behavior to simulated solar radiation by model testing.

Theoretically, the non-uniform temperature fields so produced are similar. However, due to unavoidable modeling errors as a consequence of material property variation, inaccuracies in model fabrication, changes in thermal contact resistances, etc., departures from exact similarity always exists. The latter can be clearly seen from the measured data which are presented in the next section. When the errors are small, as they indeed were in our investigation, a simple correction is possible by assuming that their effects are additive.

At the end of the initial heating period; the test object was again irradiated by the simulated solar beam in precisely the same manner as the first test series. The time of beam irradiation was again 60 minutes for the prototype and 48.78 minutes for the model. When this was done, both the heater current and the beam radiation were quickly and simultaneously interrupted. All thermocouple outputs were continuously monitored as the system temperature dropped.

Throughout the heating phase of the tests, the electric heater power was maintained constant. To achieve this, it was found necessary to make some minor adjustment of the heater voltage in order to

Table II Heater Power used in Second Test Series

	Prototype	One-half Scale Model
Net Heater Power Btu/hr	106.9	27.1
Heating Time min.	100.0	81.3

(Model Area Ratio = 0.253; Model Time Scale = 0.813) compensate the change in resistance as the temperature rose. All test data were taken with chamber pressure maintained at approximately 5 X 10^{-7} torr and the shroud surface indicating temperatures ranging from -310°F for its lower and middle portion to -270°F for its upper portion.

4. TEST RESULTS

4.1 Series A Results--all surfaces coated with Cat-A-Lac black paint

The measured temperature-time histories at five homologous thermocouple locations are shown in Figs. 8-1 through 8-5 for material (1) and in Figs. 9-1 through 9-5 for material (2). The latter was the surface receiving the beam radiation. Data recorded from the remaining thermocouples are of similar nature. Two groups of curves are displayed in each figure. Those at the lower temperature level were obtained under the condition of uniform initial temperature distribution and with the simulated solar beam as the sole heating source. The upward and downward arrows indicate, respectively, the beginning and the end of the beam irradiation. It should be noted that, subsequent to the interruption of the beam radiation, all thermocouples of material (1) continued to exhibit rising temperatures for some time before they eventually dropped. This is obviously due to the transfer of heat from the higher temperature surface (2) by radiation and conduction which more than offsets the heat loss to the surrounding shroud. The conditions were clearly different for material (2). At locations adjacent to the irradiated area, the temperatures dropped virtually immediately when the beam was interrupted. Thermocouples

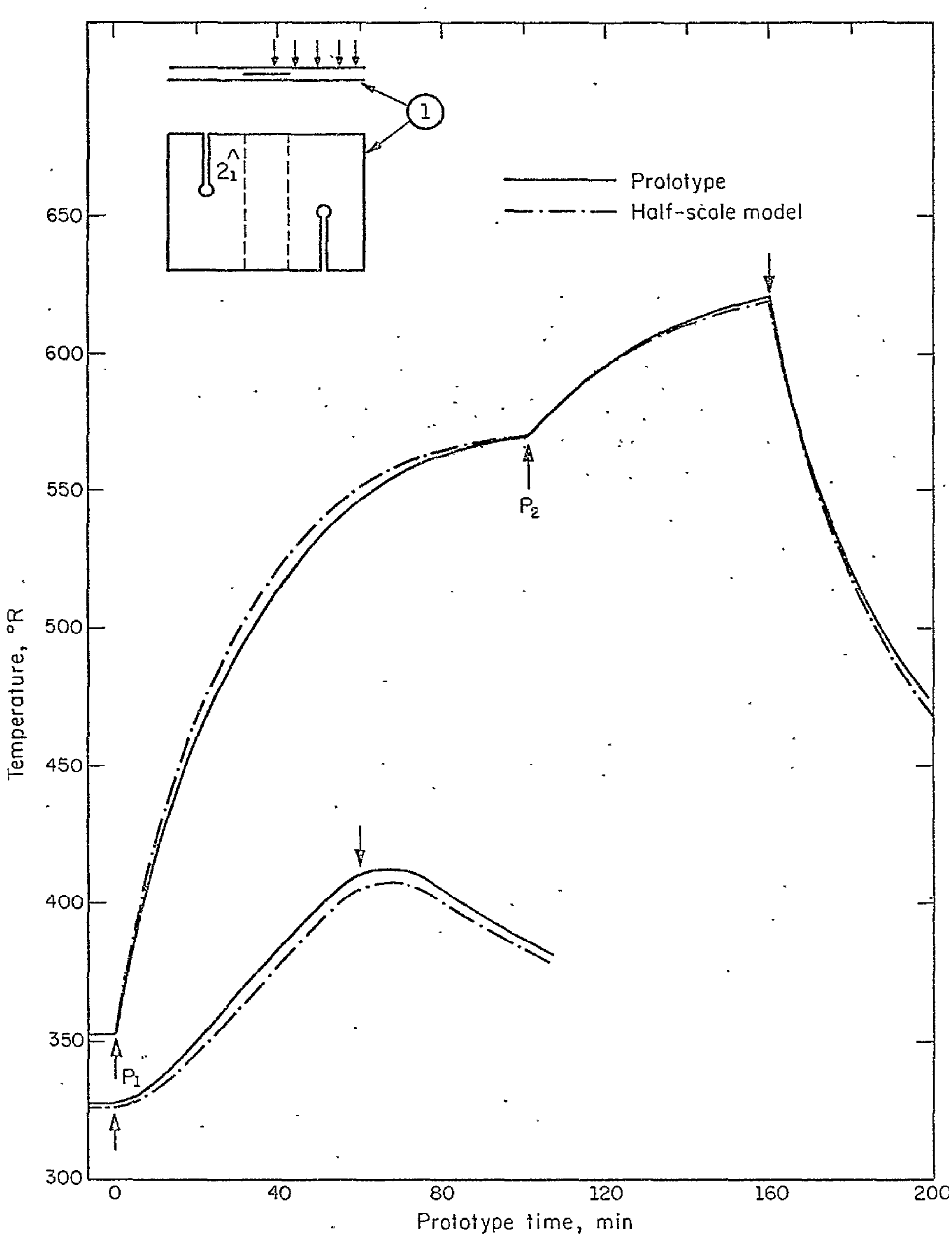


Fig. 8-1 Heating and Cooling Transient at Location 2_1-Series A

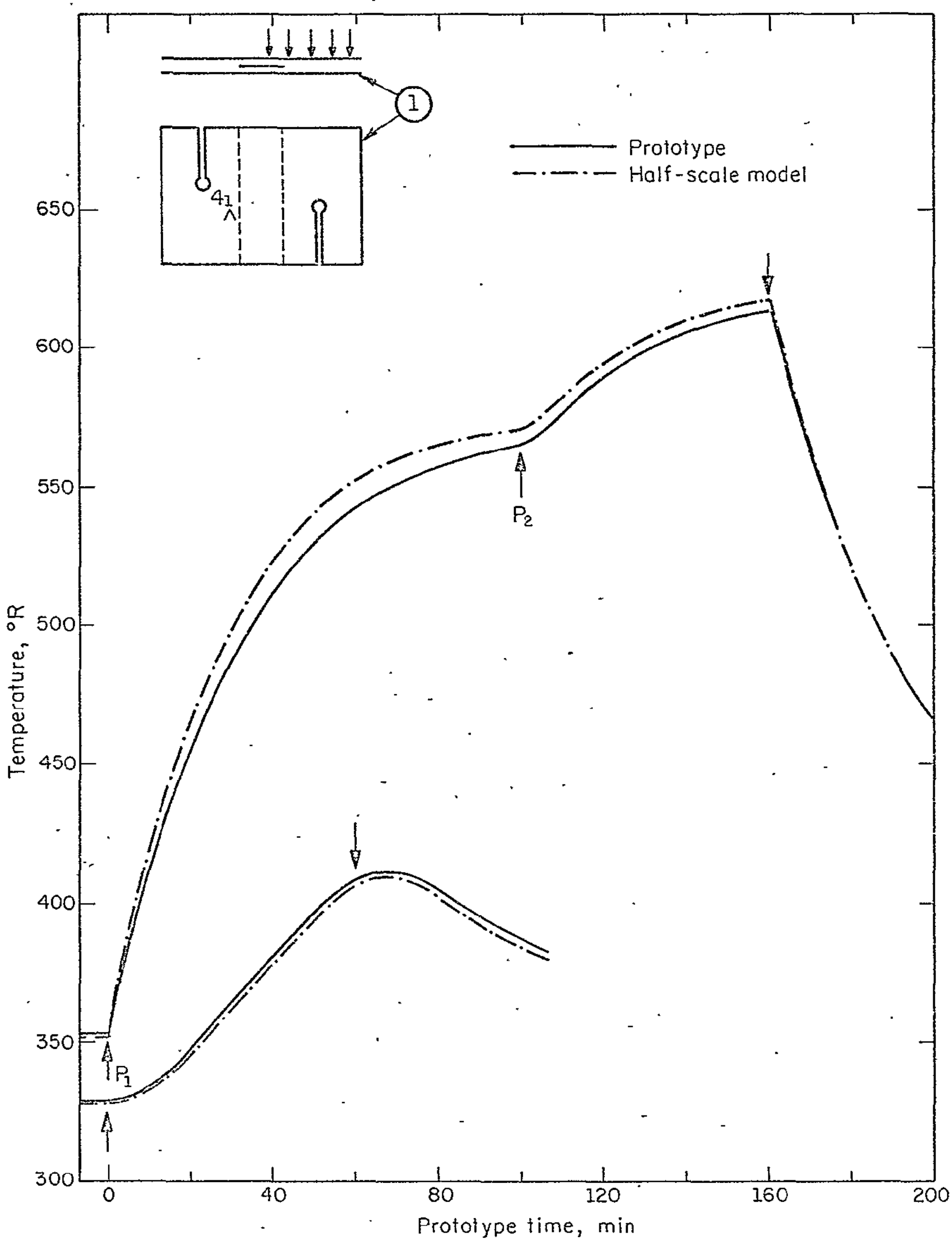


Fig. 8-2 Heating and Cooling Transient at Location 4_1-Series A

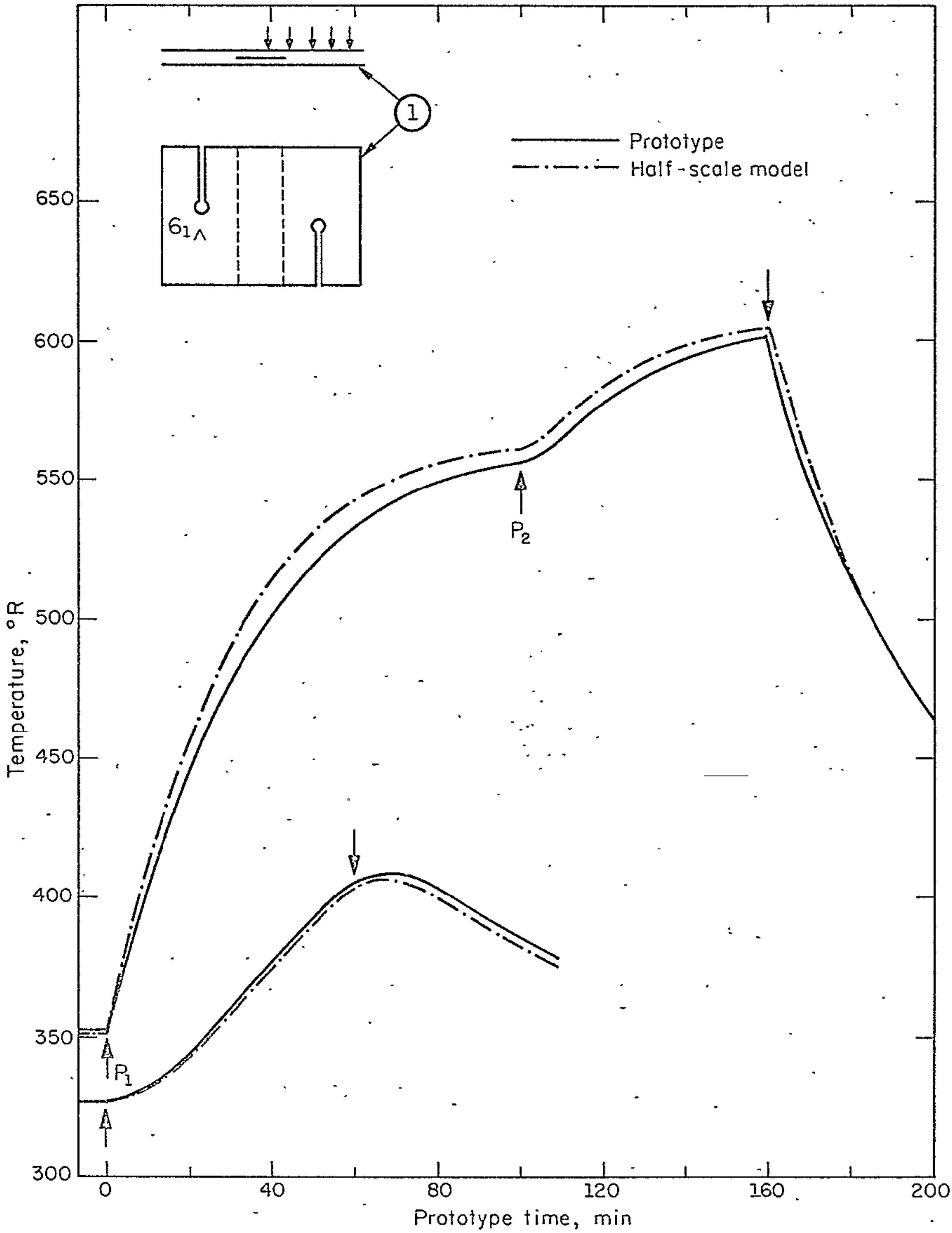


Fig. 8-3 Heating and Cooling Transient at Location 6_1-Series A

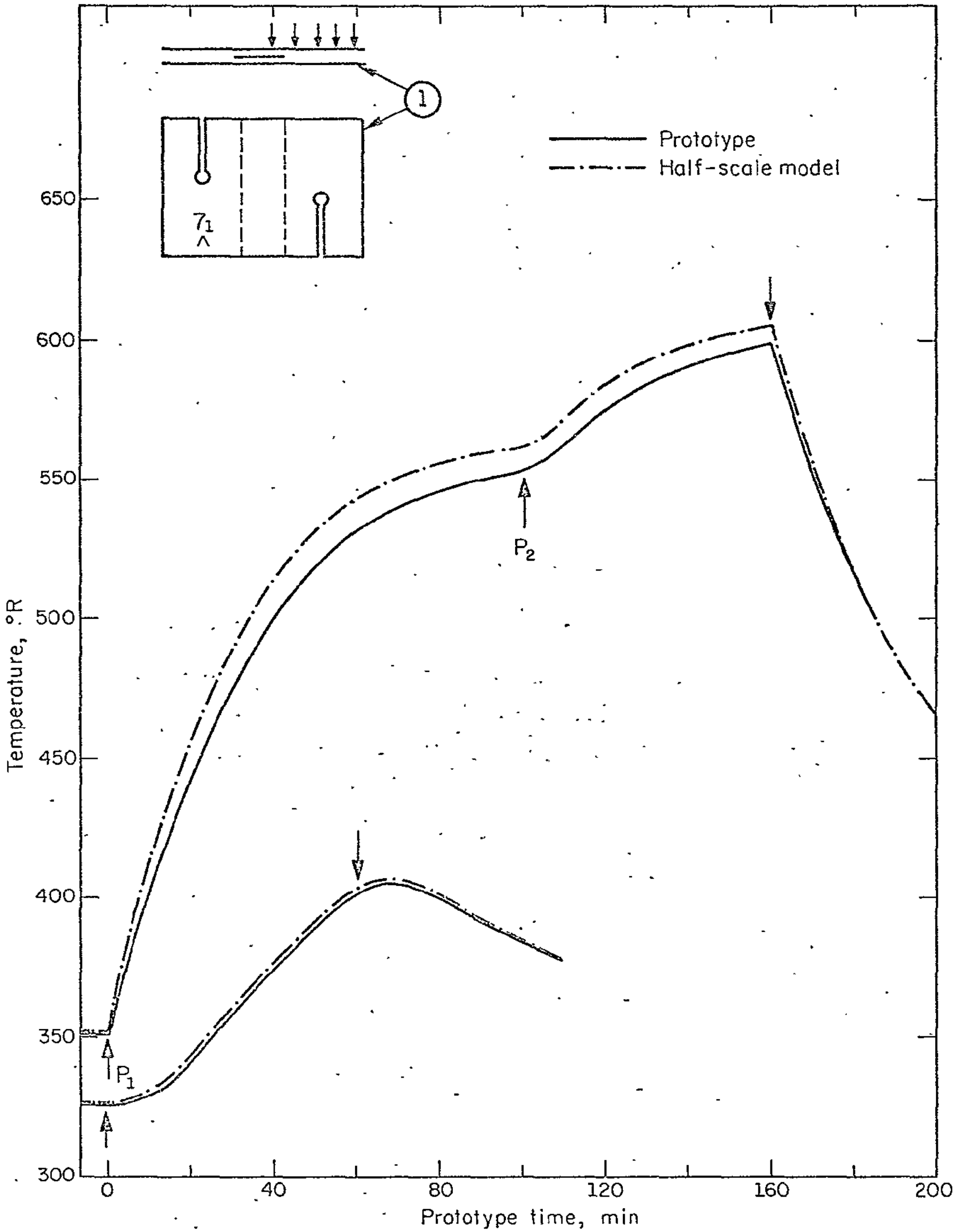


Fig. 8-4 Heating and Cooling Transient at Location 7_1-Series A

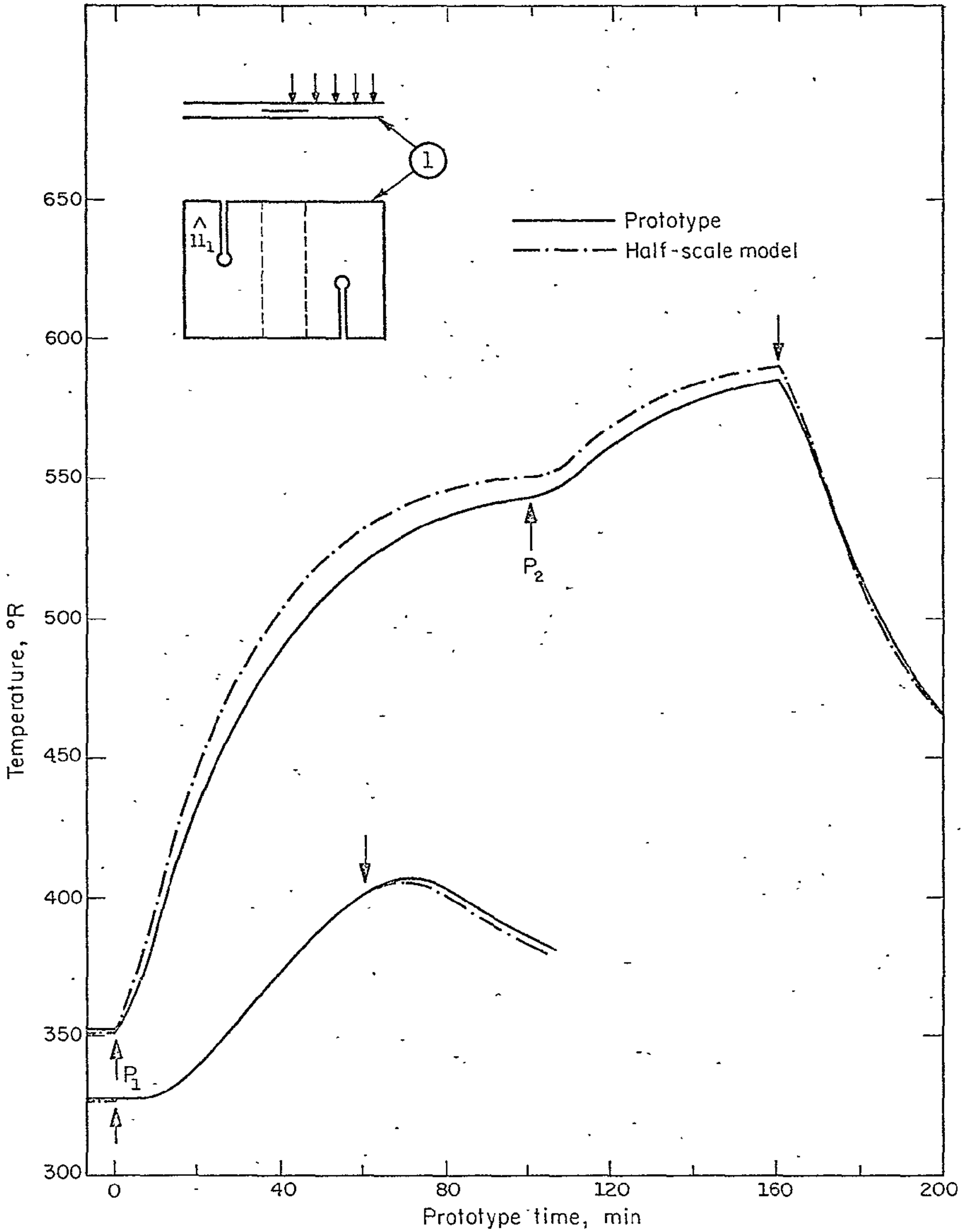


Fig. 8-5 Heating and Cooling Transient at Location 11_1-Series A

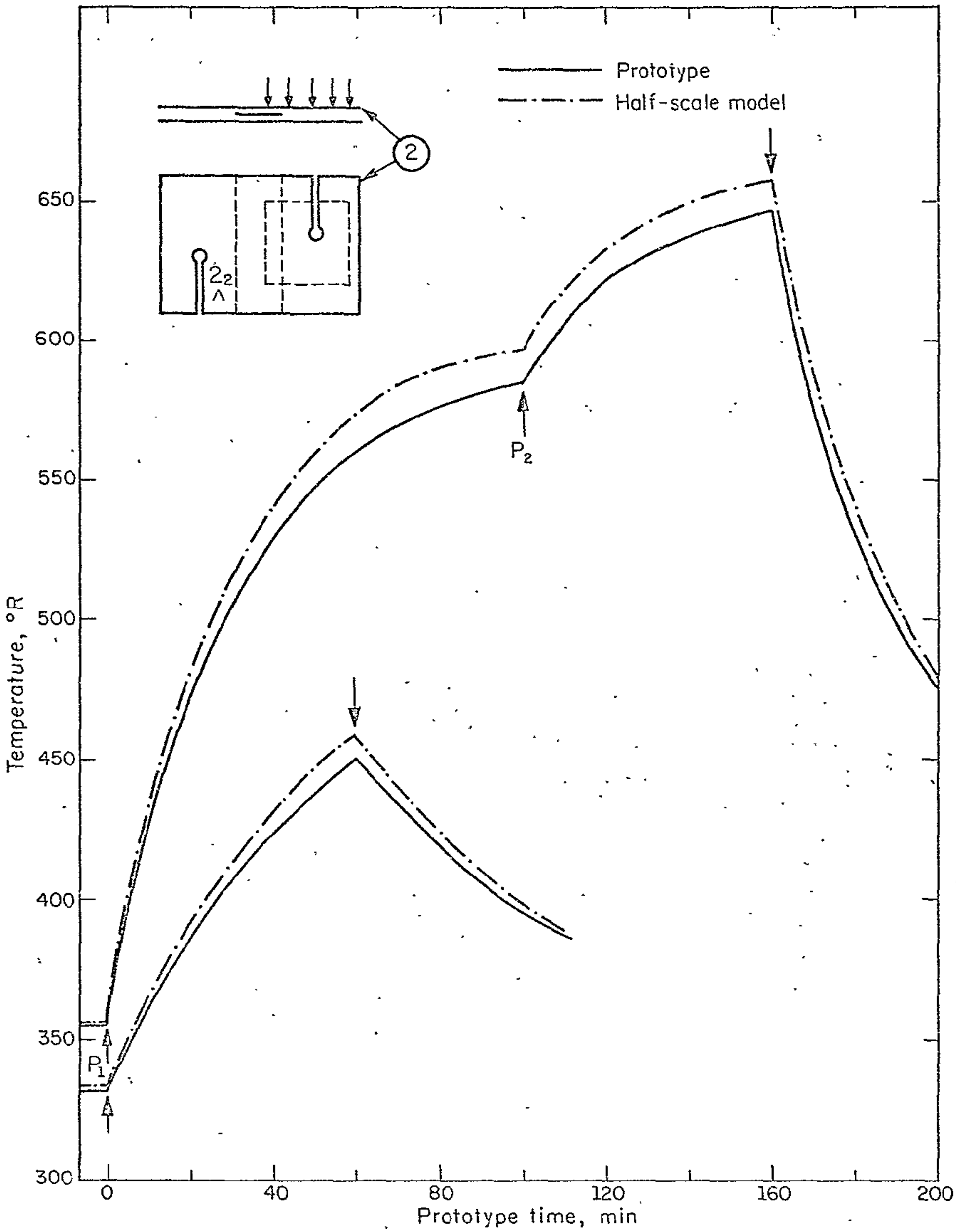


Fig. 9-1 Heating and Cooling Transient at Location 2_2-Series A

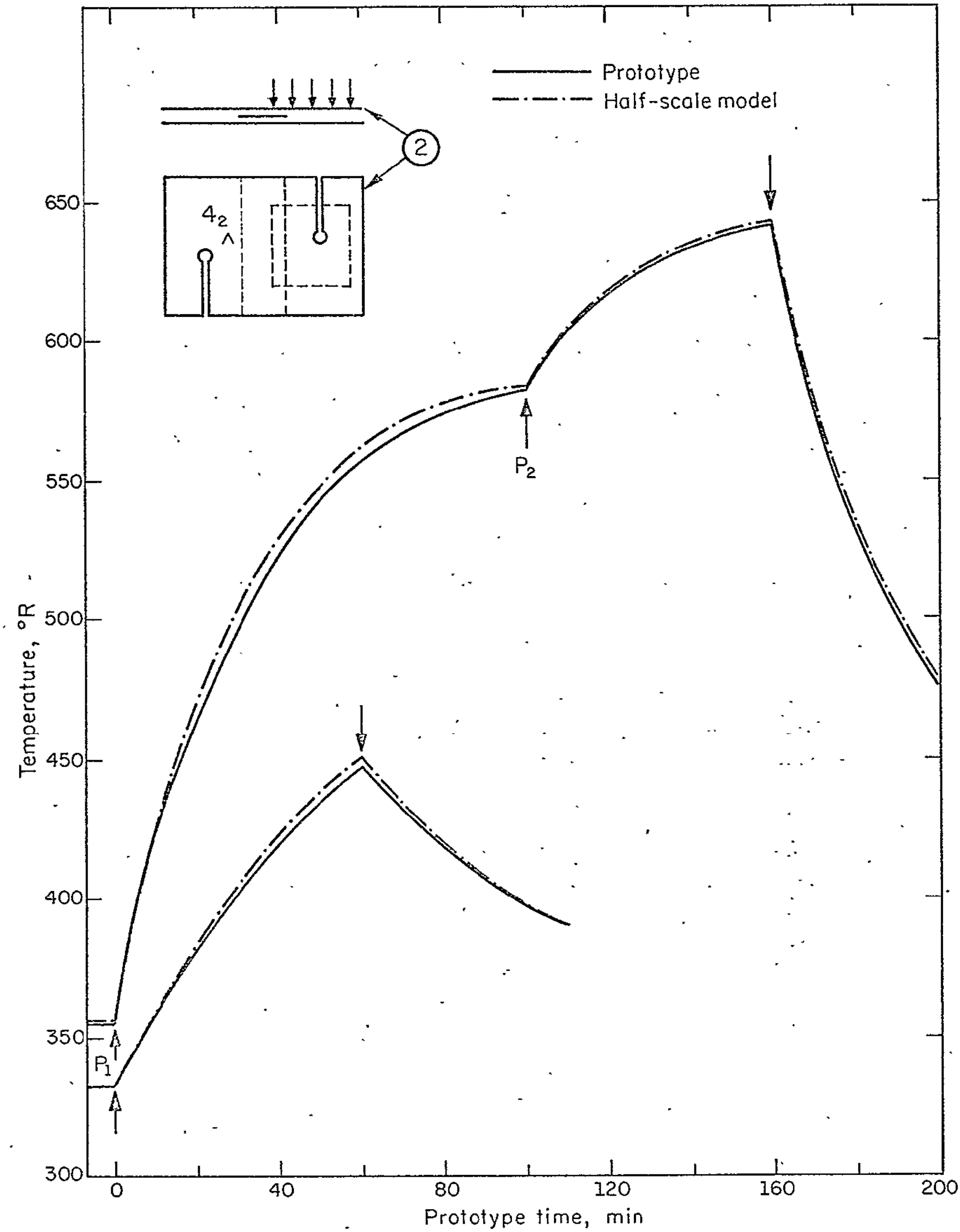


Fig. 9-2 Heating and Cooling Transient at Location 4_2-Series A

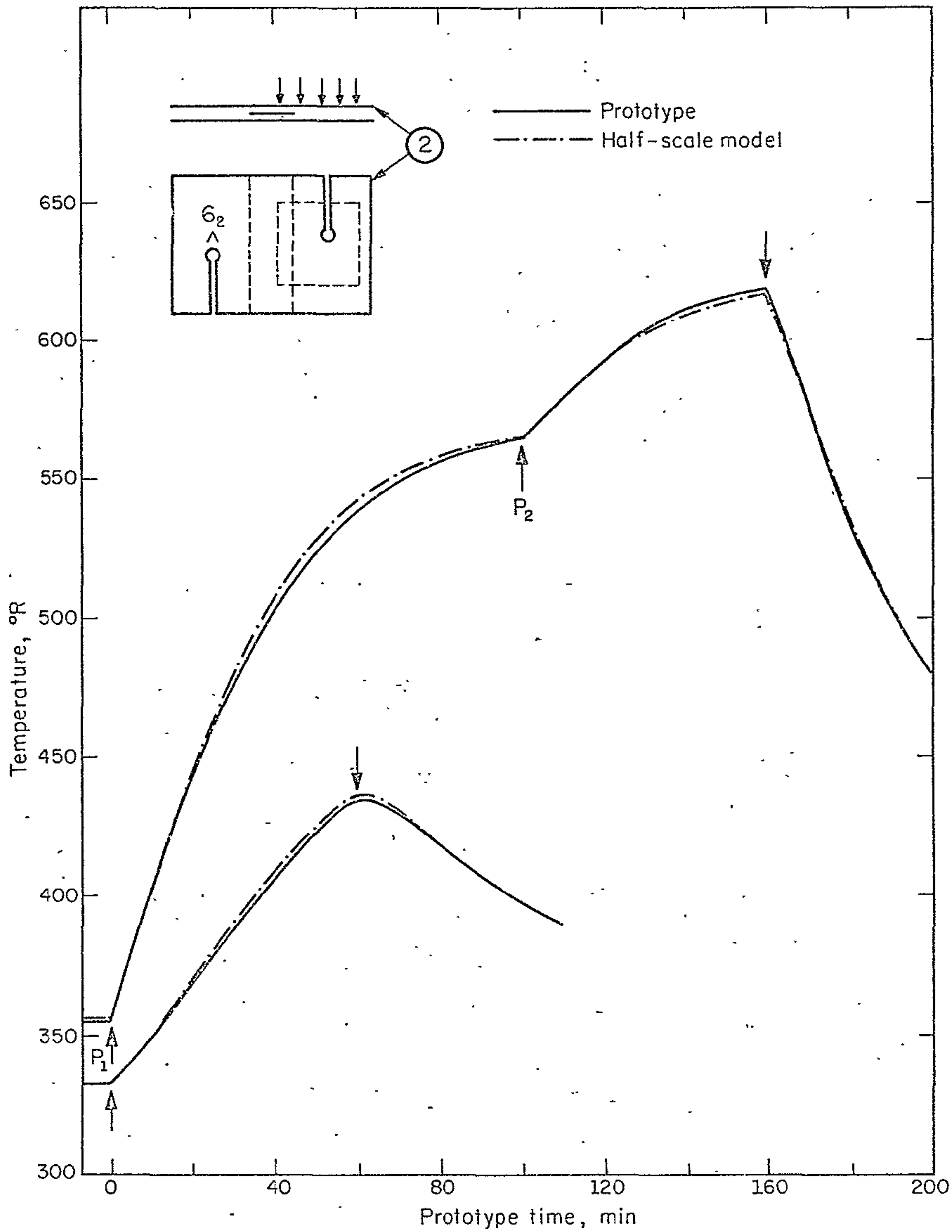


Fig. 9-3 Heating and Cooling Transient at Location 6_2-Series A

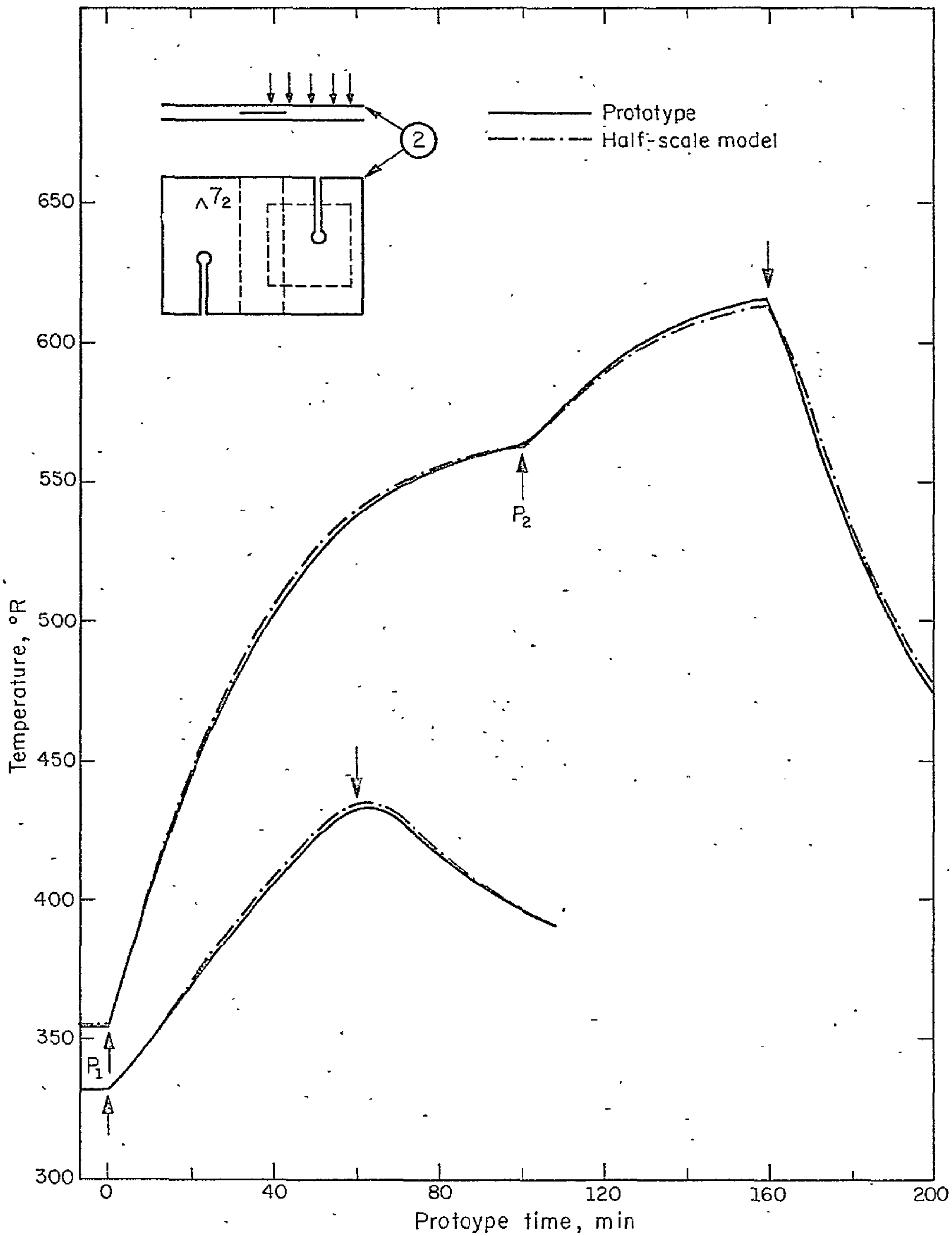


Fig. 9-4 Heating and Cooling Transient at Location 7_2-Series A

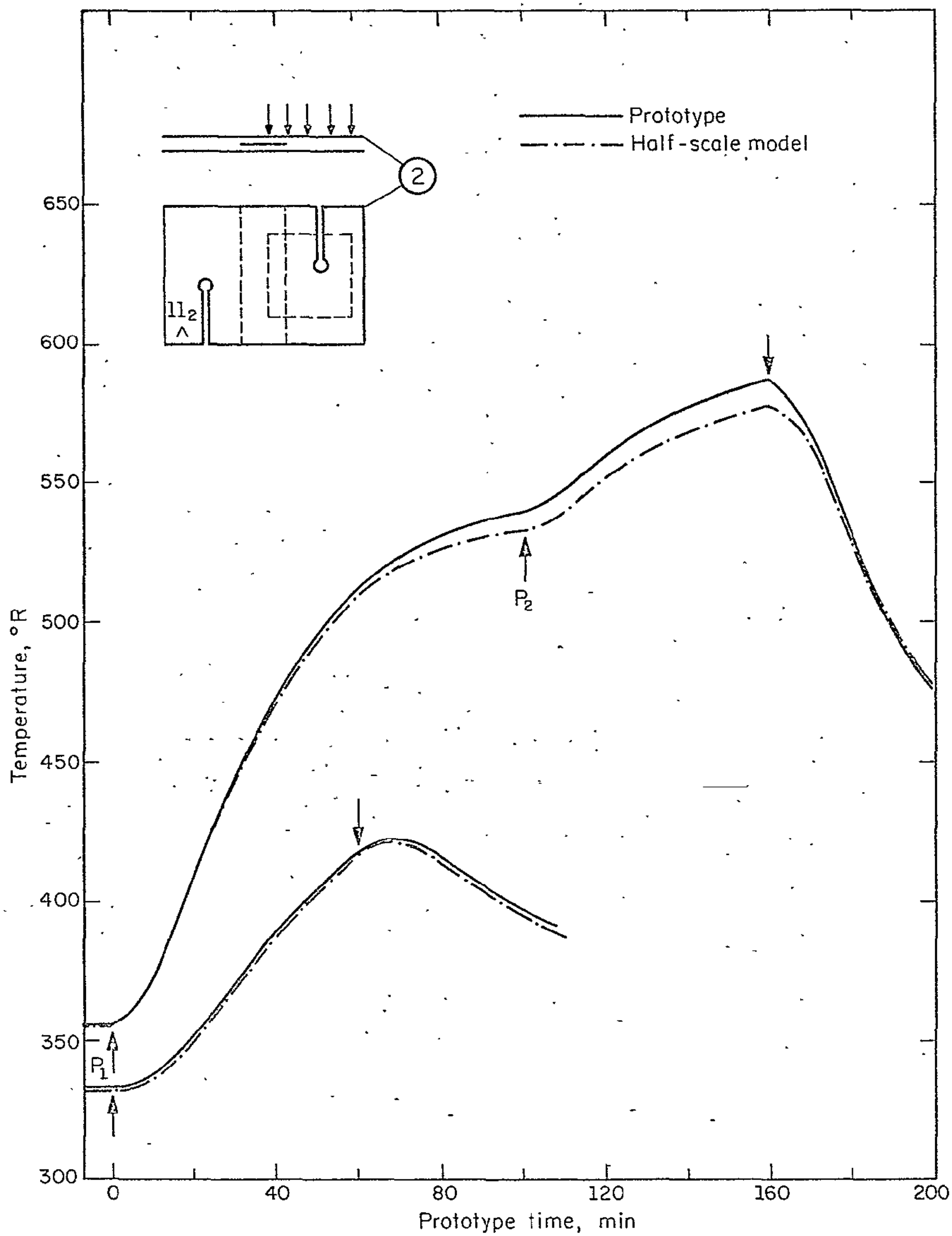


Fig. 9-5 Heating and Cooling Transient at Location 11_2-Series A

2_2 and 4_2 exhibited such behavior. The local temperatures within the irradiated region would, no doubt, experience an even faster rate of decline. On the other hand, thermocouples at location 7_2 and 11_2, both of which were relatively remote from the irradiated area and were well within the shaded region, showed continuing rise of temperature for several minutes prior to their eventual fall, as one might expect.

The second group of curves pertains to the test run in which the system was first heated electrically, beginning at the instant marked by the upward arrow P_1. The instant when the test object was exposed to the simulated solar beam was indicated by the arrow P_2. The downward arrow designates the instant when both heating sources were removed. In all figures, the abscissa is the prototype time which, in the case of the model, is the actual time divided by 0.813, the model time scale.

As stated earlier, the main purpose of the second phase of the present research was to further evaluate the proposed modeling technique, namely, the manufacture of "effective" conductivity and the utilization of thickness distortion, when the system is subjected to simulated solar beam irradiation. The minor discrepancies exhibited by the temperature-time plots in Figs. 8 and 9 are, of course, the consequence of all error sources. While it is not possible to sort out those associated only with the beam radiation, a crude estimate can nevertheless be made. For reasons already given, the initial* temperature fields produced by electric heating in the prototype and in the model were not strictly similar. Since the rate of temperature change with time was then relatively small, it appears reasonable, at least as an approximation, to simply subtract such

*This refers to the instant immediately prior to the admission of the solar beam.

initial errors from the recorded temperature readings at the end of beam irradiation. It was on this premise that Table III was prepared. The errors are believed to be random in nature and no significance should be attached to the sign shown. The average error was computed without reference to sign and it provides a more meaningful measure of the modeling accuracy. From the curves of Figs. 8 to 9 and the data listed in Table III, one sees that the prediction accuracy of models, when subjected to beam radiation, is at least as good, if not better, as when only electric heating is involved. The two largest errors, which amounted to about 12°R, occurred at location 5_1 and 2_2. The overall average error is within 6°R and that associated with beam radiation is probably no more than 3°R.

Subsequent to the removal of the heater current and the beam radiation, there was a rapid descent in all temperatures due to the relatively high rate of heat transfer to the surrounding cold, black shroud surface. In all cases, the cooling curves obtained with the model match quite well with those obtained with the prototype.

4.2 Series B Results--beam irradiated surface coated with PV-100 white paint.

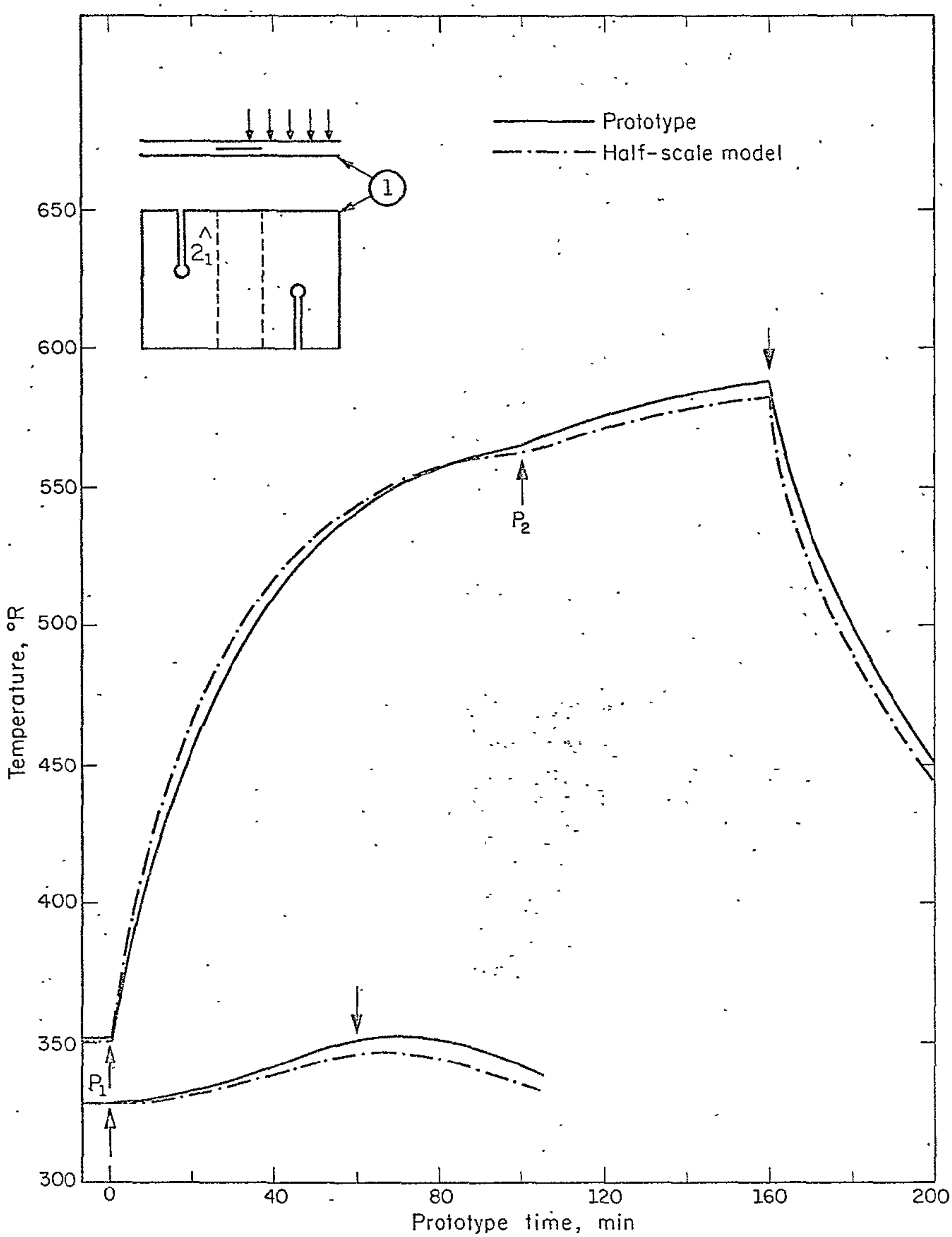
To further examine the performance of the model, one surface of material 2 was coated with PV-100 white paint which is a silicon alkyd coating, known to exhibit high infrared emittance and relatively low ultraviolet absorptance. The Cat-A-Lac black coating on the remaining surfaces of the test object was not disturbed. The measured temperature-time histories at five homologous locations are shown in Figs. 10-1 through 10-5 for material 1 and in Figs. 11-1 through 11-5 for material 2.

TABLE III

Estimates of Temperature Prediction Errors
(All surfaces coated with Cat-A-Lac black paint:
nonuniform initial temperature distribution)

Thermocouple Number	Temperature, °R		
	Initial Error	Final Error	Probable Error Associated with Beam Radiation
		Material (1)	
1_1	- 2.7	-3.0	0.3
2_1	+ 0.7	-2.7	3.4
3_1	+ 4.7	+2.6	2.1
4_1	+ 6.3	+3.4	2.9
5_1	+11.3	+9.4	1.9
6_1	+ 5.0	+2.3	2.7
7_1	+ 8.4	+5.4	3.0
8_1	+ 6.7	+5.0	1.7
9_1	+ 7.0	+4.4	2.6
10_1	+ 3.7	0	3.7
11_1	+ 7.0	+4.3	2.7
Average:	5.8	3.9	2.5
		Material (2)	
1_2	+10	+ 9.0	1.0
2_2	+12.6	+12.3	0.3
3_2	+ 6.7	+ 5.3	1.4
4_2	+ 2.0	+ 0.4	1.6
5_2	+ 0.8	- 1.4	2.2
6_2	0	- 2.3	2.3
7_2	- 1.0	- 3.3	2.3
8_2	- 1.7	- 4.7	3.0
9_2	+ 1.0	- 2.7	3.7
10_2	+ 1.0	- 0.3	1.3
11_2	- 6.7	-10.3	3.6
Average:	4.0	4.7	2.1

Plus sign refers to model temperatures which are too high.



Fog. 10-1 Heating and Cooling Transient at Location 2_1-Series B

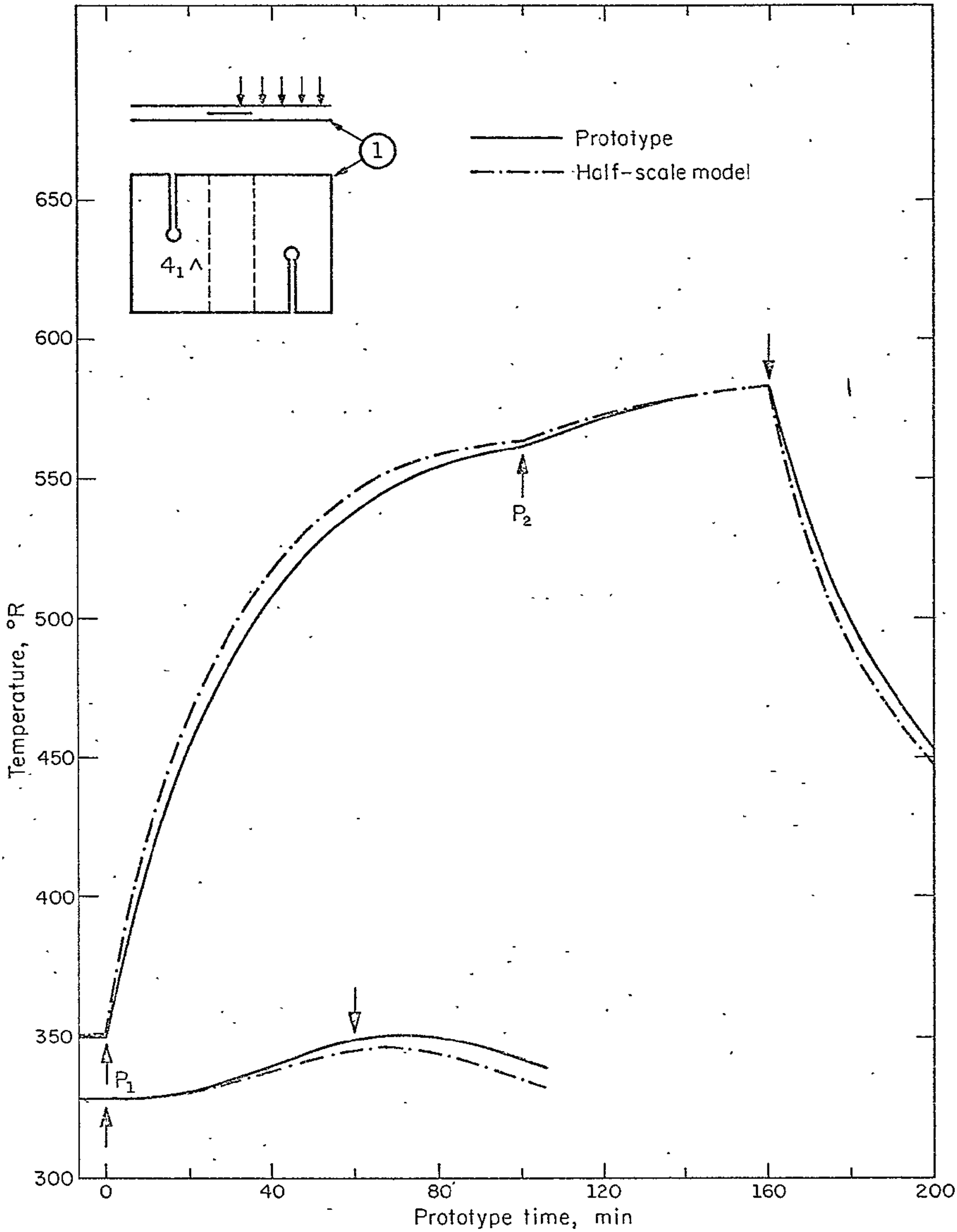


Fig. 10-2 Heating and Cooling Transient at Location 4_1-Series B

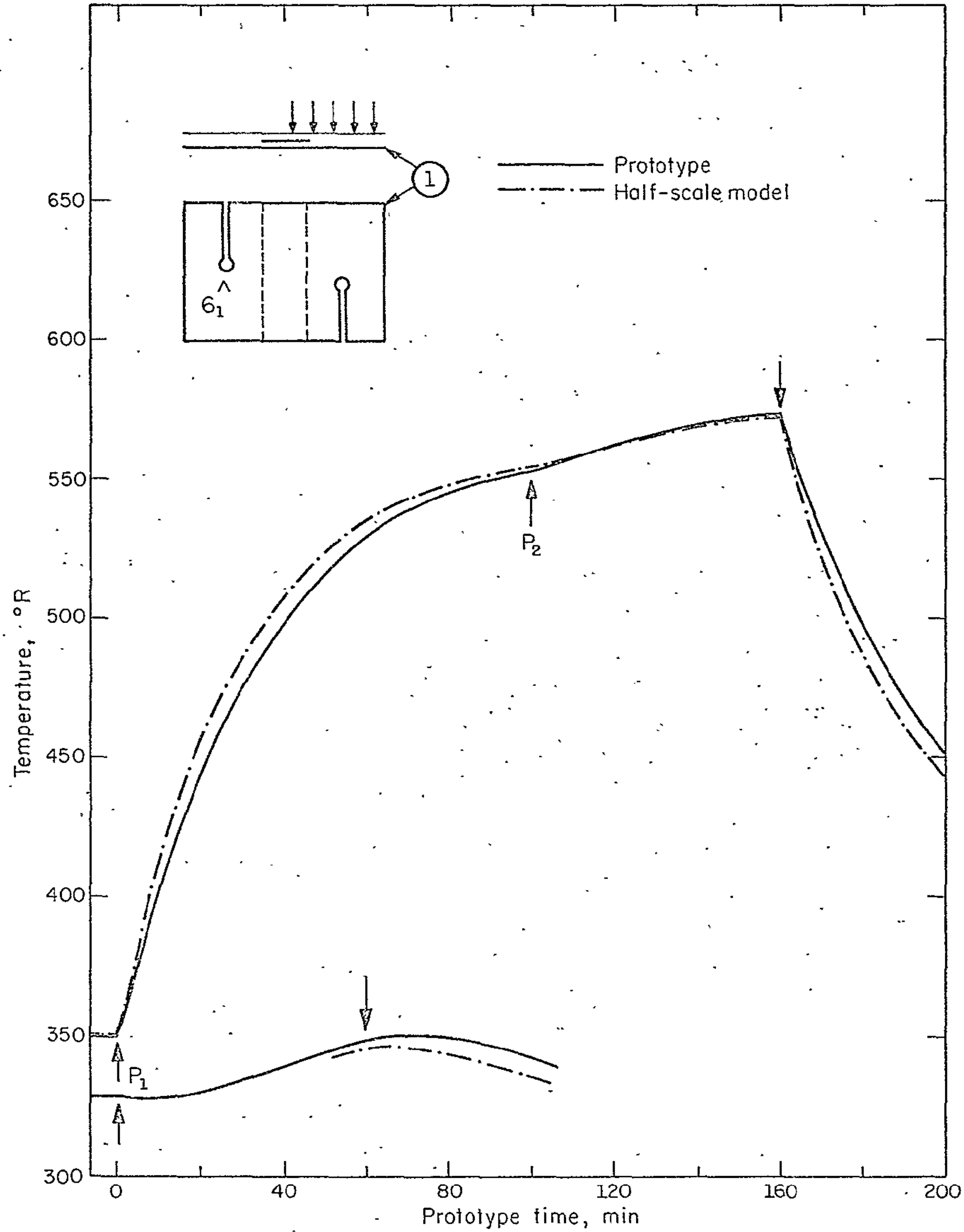


Fig. 10-3 Heating and Cooling Transient at Location 6_1-Series B

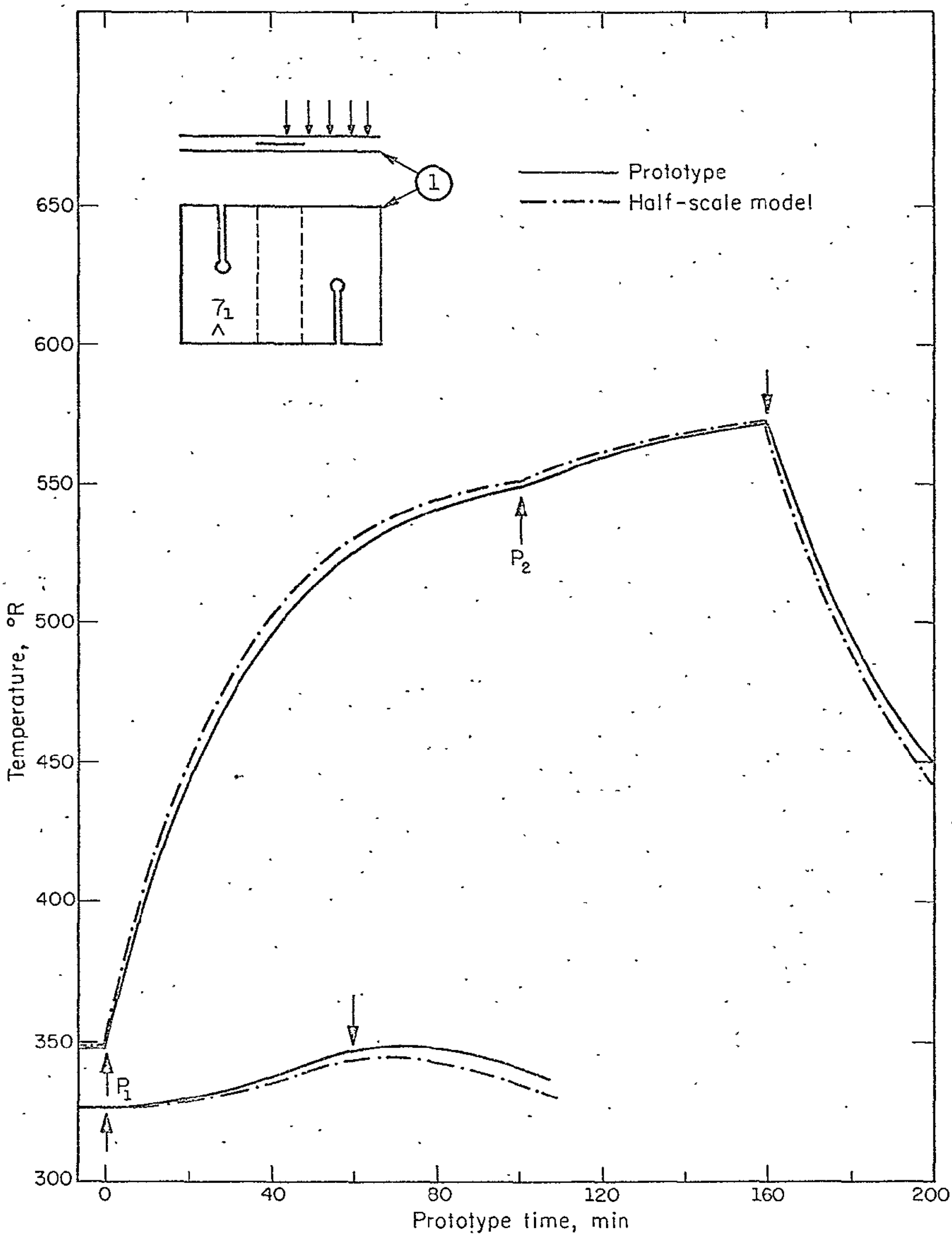


Fig. 10-4 Heating and Cooling Transient at Location 7_1-Series B

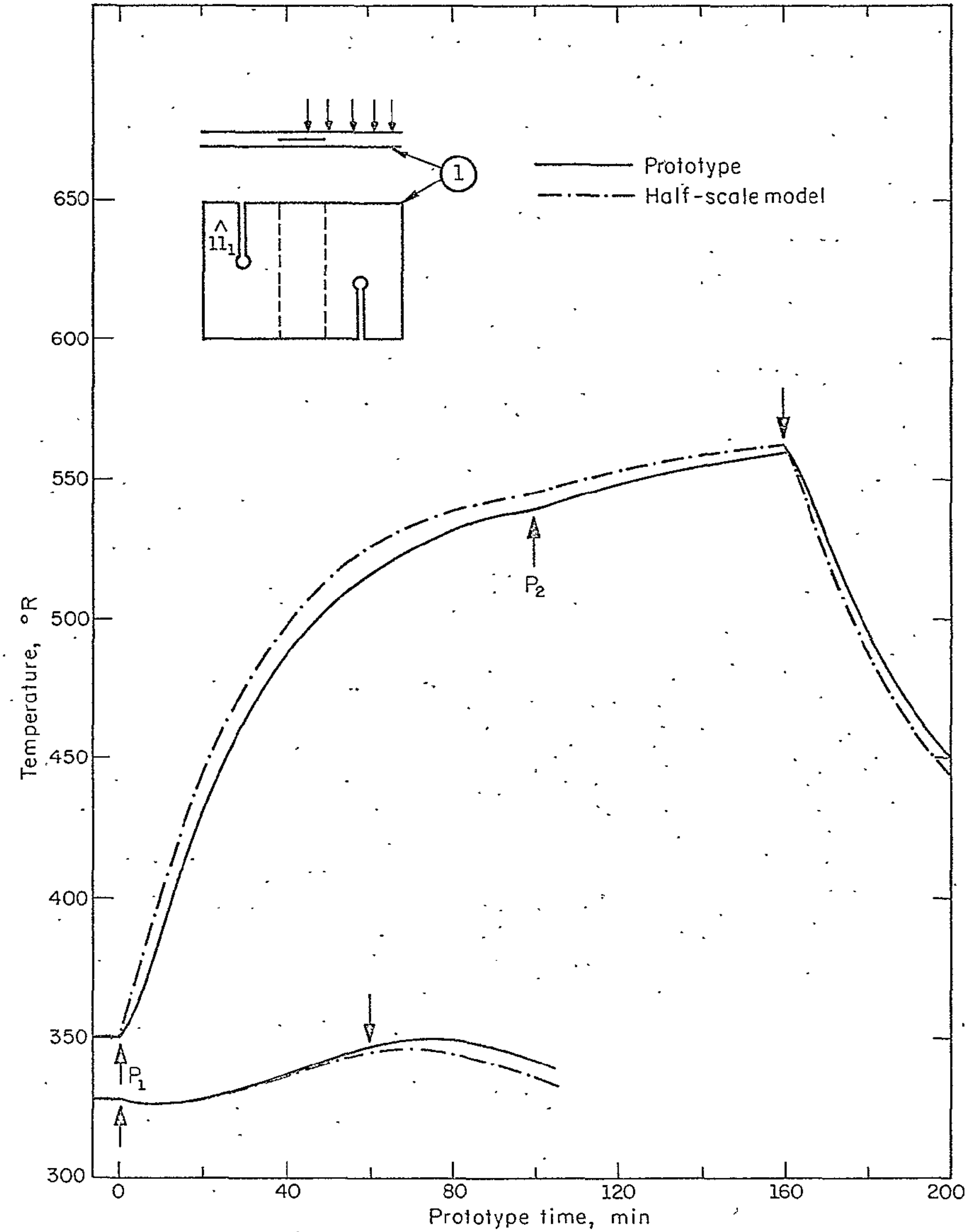


Fig. 10-5 Heating and Cooling Transient at Location 11_1-Series B

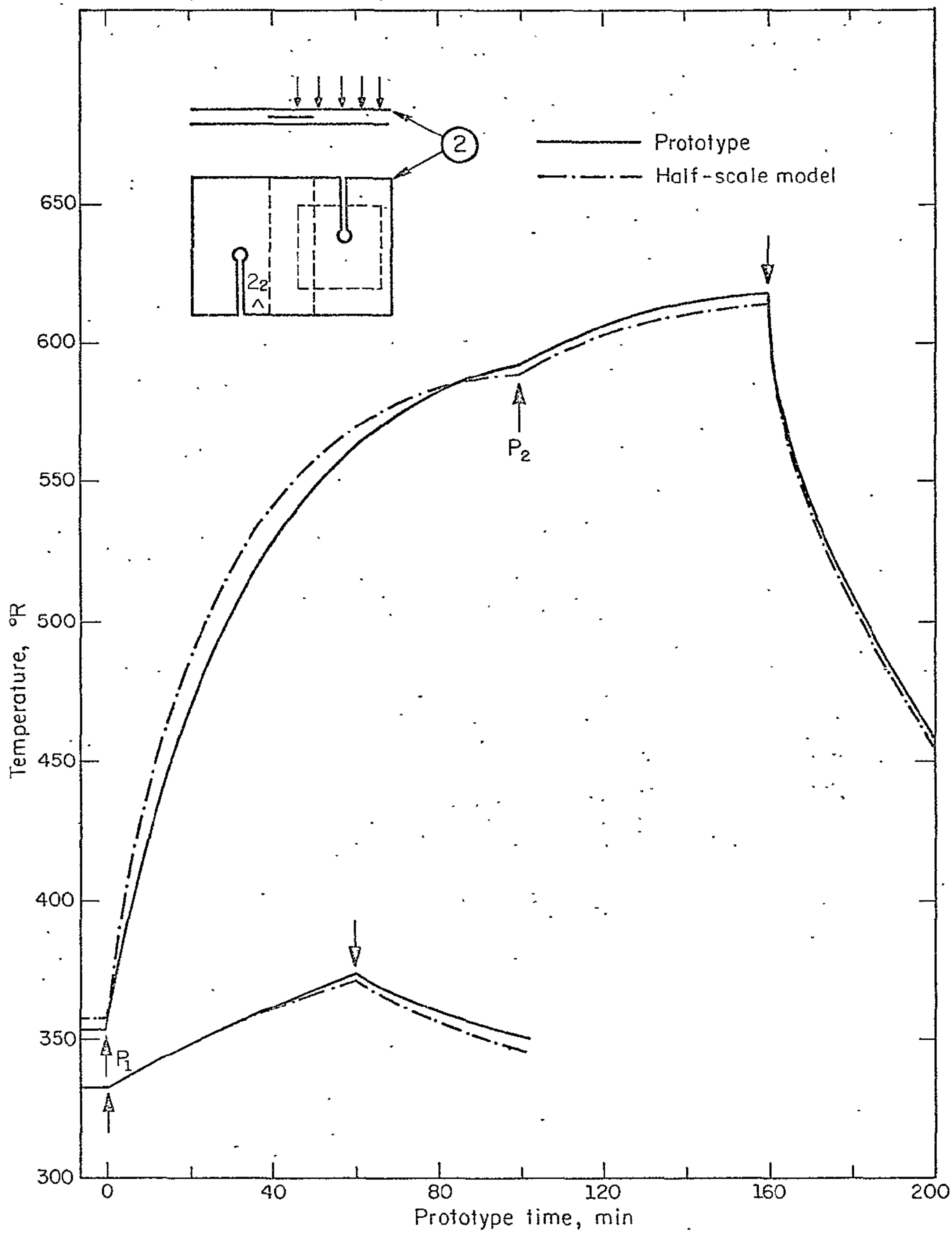


Fig. 11-1 Heating and Cooling Transient at Location 2_2-Series B

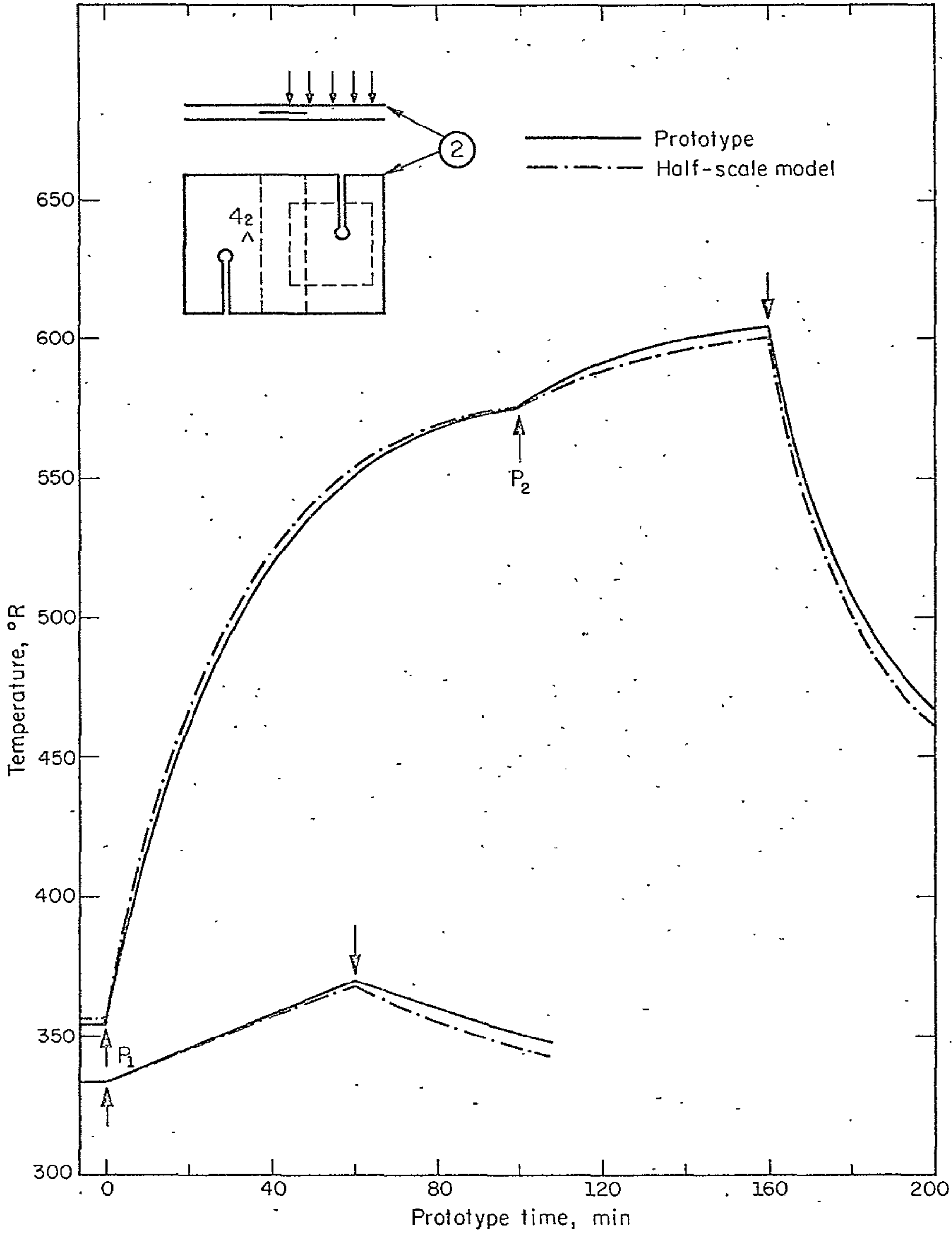


Fig. 11-2 Heating and Cooling Transient at Location 4_2-Series B

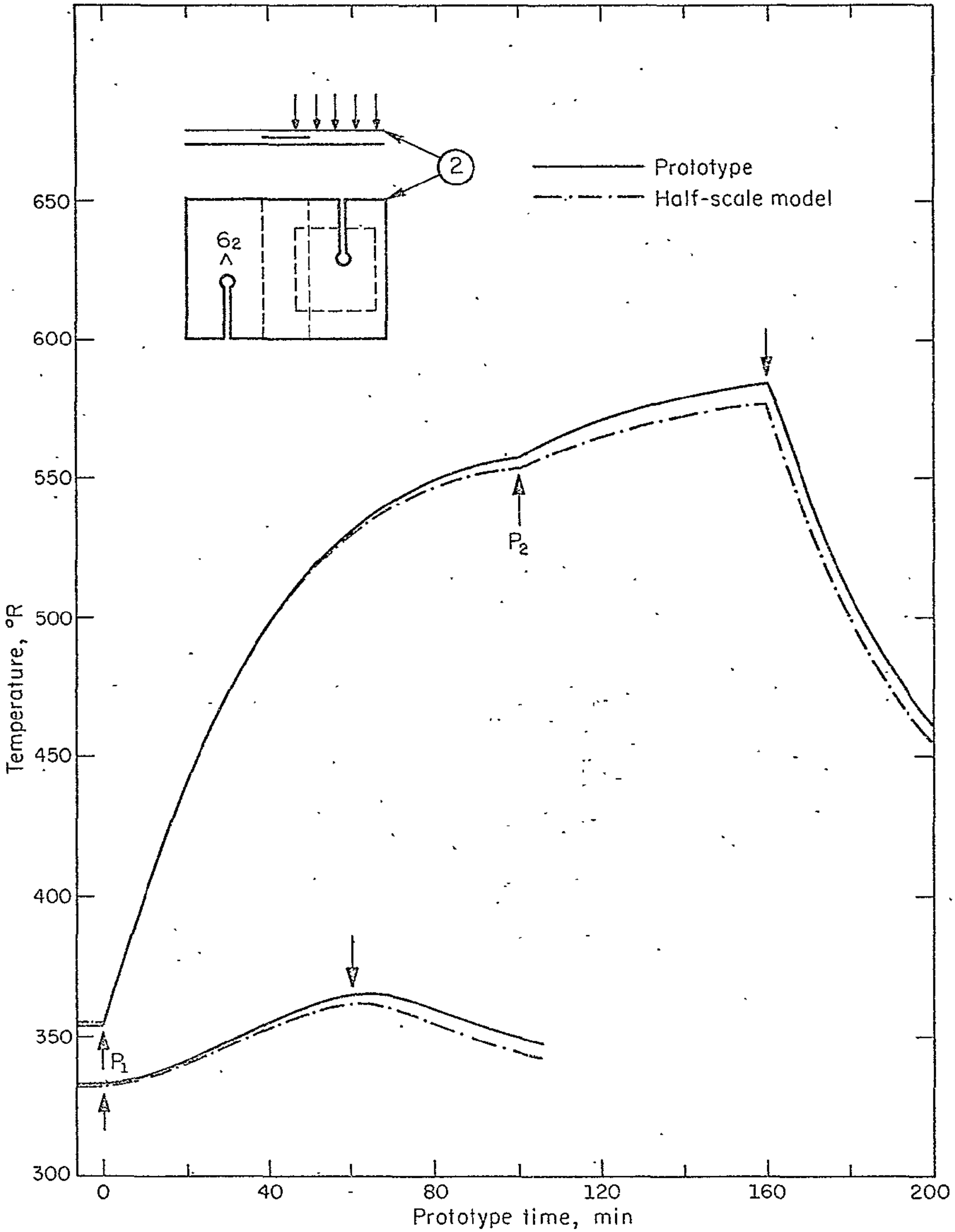


Fig. 11-3 Heating and Cooling Transient at Location 6_2-Series B

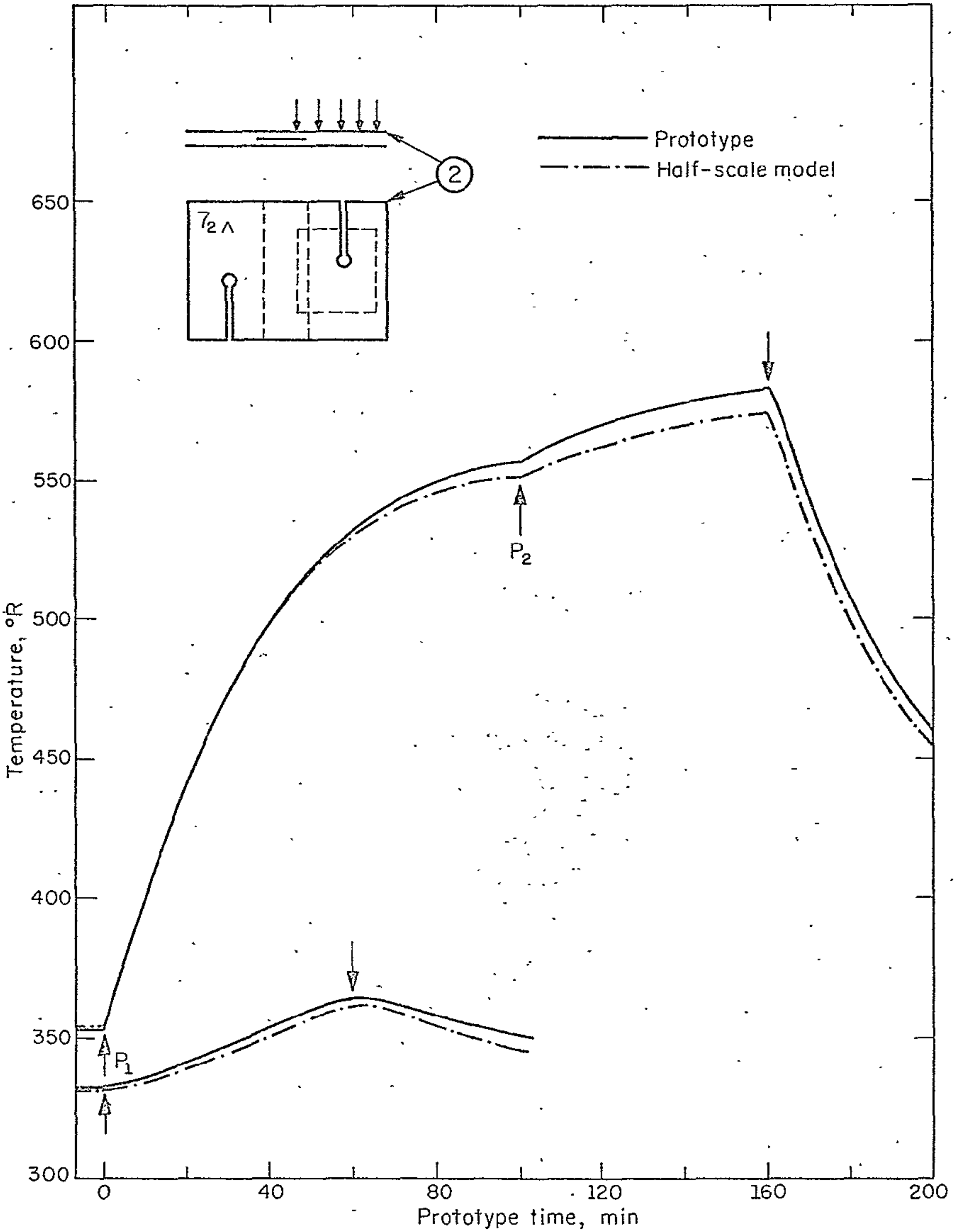


Fig. 11-4 Heating and Cooling Transient at Location 7_2-Series B

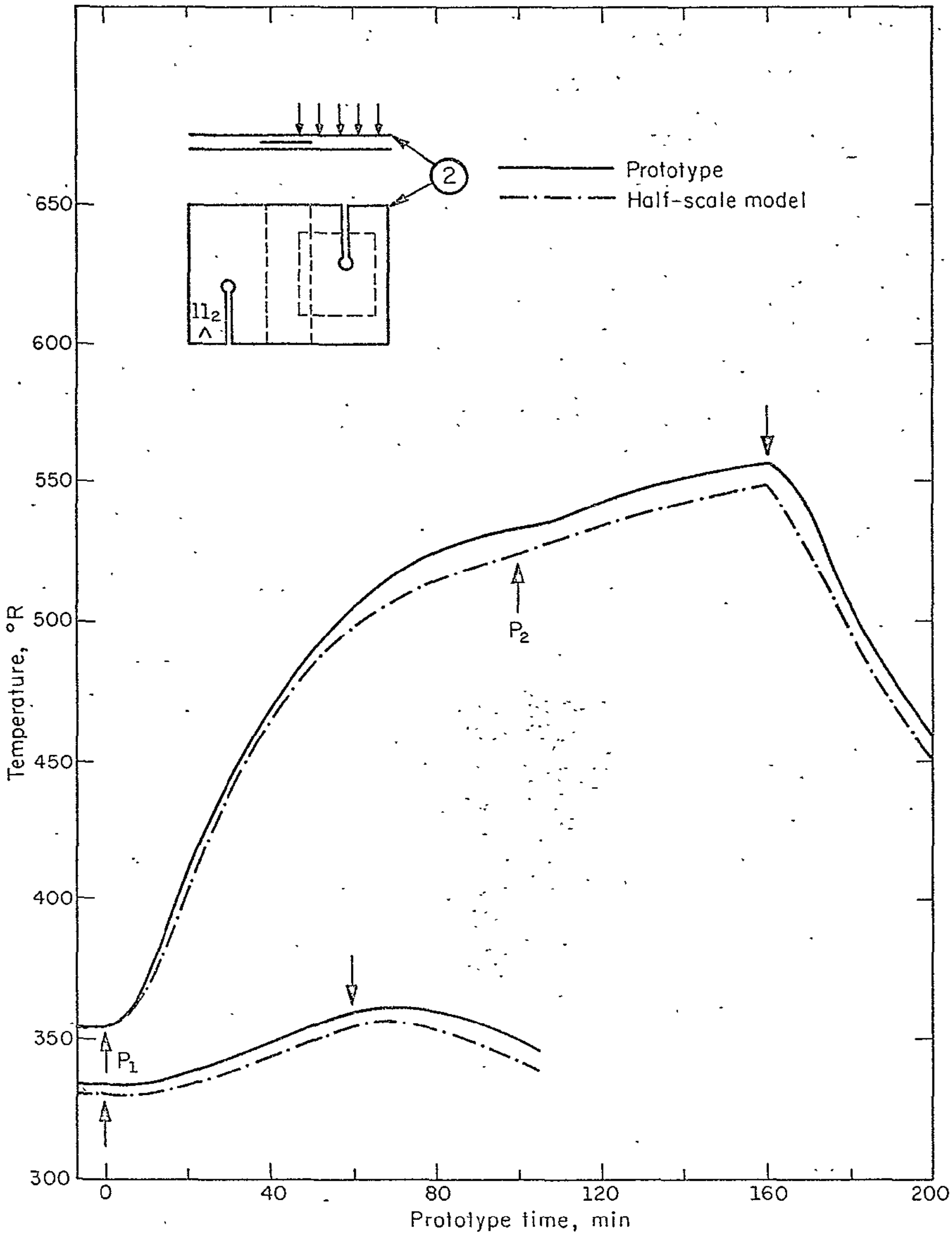


Fig. 11-5 Heating and Cooling Transient at Location 11_2-Series B

As in the test series A, the latter was the surface receiving beam radiation. All symbols have the same meaning as those shown in Figs. 8 and 9. The discussion given in the previous section for Series A results is generally applicable here, including the data listed in Table IV. If one compares the present results with those obtained in the earlier test series, the low absorptance of the white paint with respect to the beam radiation is evident. Insofar as modeling accuracy is concerned, no noticeable difference exists.

4.3 Reproducibility of Test Data

When all surfaces of the test object were coated with Cat-A-Lac black paint, very good reproducibility of the measured temperature transients could generally be obtained. The highly stable surface radiation property of the black paint has been noted previously*. To ascertain if the PV-100 white paint affords similar stable surface character, additional tests were conducted. Figure 12 illustrates one instance of the many measured results. The time interval between the two test runs was approximately three weeks. Taking all observed data into consideration, it can be stated that the reproducibility is very good and is generally within 2°R.

5. CONCLUSIONS AND RECOMMENDATIONS

Based on the experimental evidence obtained in the present investigation and others previously reported, the following conclusions can be drawn:

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*Technical Report to JPL, ME-TR-JPL-951660-1 (Supplement), January, 1968.

TABLE IV

Estimates of Temperature Prediction Errors
(Simulated solar beam incident on surface coated with PV-100 white paint; nonuniform initial temperature distribution)

Thermocouple Number	Temperature, °R		
	Initial Error	Final Error	Probable Error Associated with Beam Radiation
		Material (1)	
1_1	---	---	---
2_1	- 3.4	- 6.7	3.3
3_1	+ 3.2	- 0.6	3.8
4_1	+ 2.3	- 1.4	3.7
5_1	+10.6	+ 8.0	2.6
6_1	+ 1.4	- 2.0	3.4
7_1	+ 1.3	+ 1.0	0.3
8_1	+ 5.0	+ 1.3	3.7
9_1	+ 4.6	+ 1.3	3.3
10_1	+ 2.3	- 1.0	3.3
11_1	+ 5.7	+ 2.7	3.0
Average:	4.0	2.6	3.0
		Material (2)	
1_2	+ 7.0	+ 2.7	4.3
2_2	- 3.0	- 4.0	1.0
3_2	+ 3.4	- 0.7	4.1
4_2	- 1.0	- 5.0	4.0
5_2	- 3.3	- 7.0	3.7
6_2	- 4.3	- 8.7	4.4
7_2	- 5.3	- 9.7	4.4
8_2	- 6.4	-10.3	3.9
9_2	- 4.7	- 9.0	4.3
10_2	- 4.3	- 7.8	3.5
11_2	- 8.3	- 6.3	2.0
Average:	4.6	6.5	3.6

Plus sign refers to model temperatures which are too high.

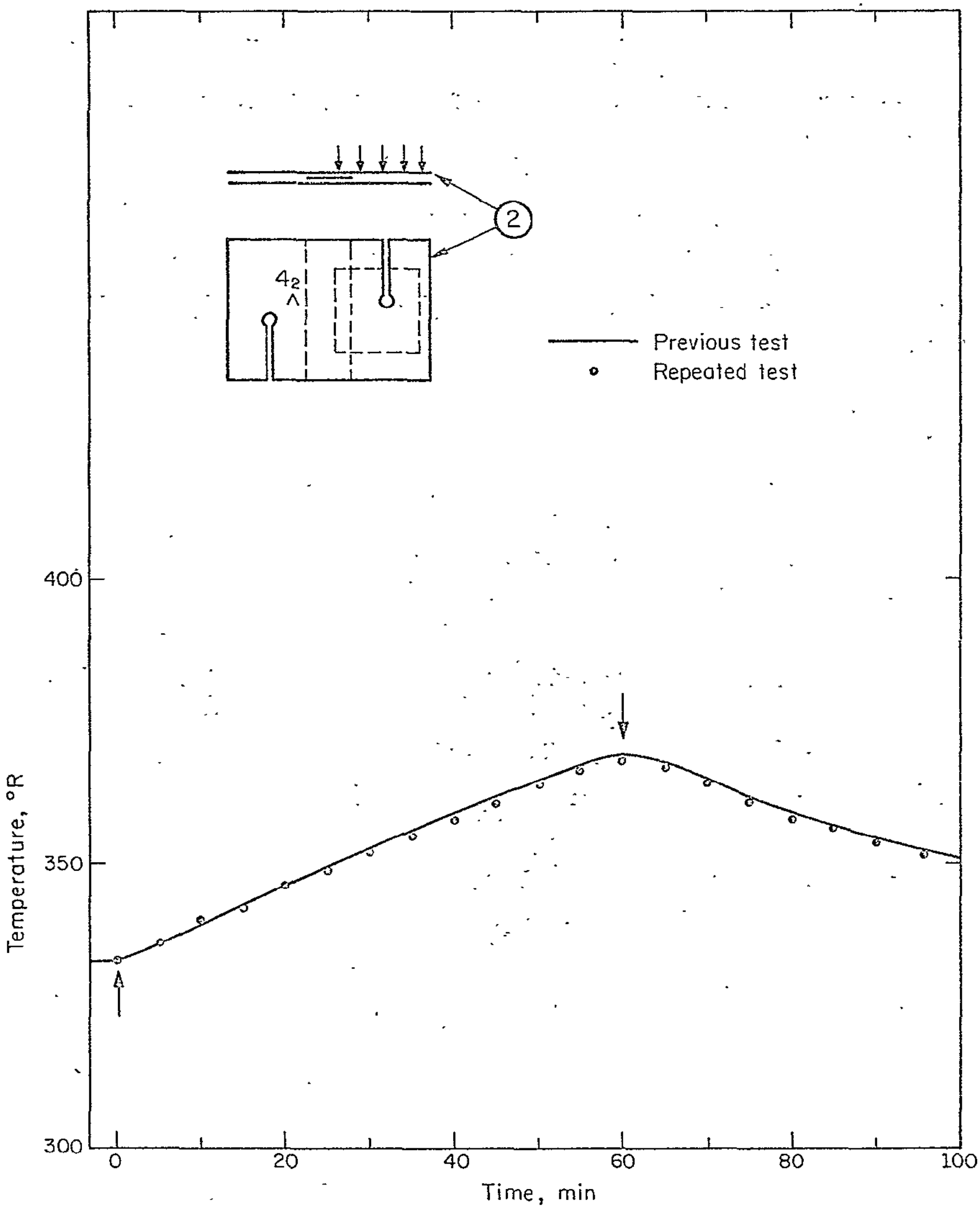

Fig. 12 Reproducibility of Temperature Measurements (Thermocouple 4_2 of Prototype)

1. The validity of the basic premise laid out in Reference [3] concerning the design of scale models for the prediction of the thermal performance of unmanned spacecrafts has been demonstrated beyond any reasonable doubt.

2. For two-dimensional systems comprising a number of different materials, the technique of satisfying transient modeling requirements by controlling the materials' effective conductivity through electroplating together with thickness distortion could yield satisfactory results. On the average, a temperature prediction accuracy of the order of 5°R is obtainable, notwithstanding that the heating source varies from an electric resistance heater to a simulated solar beam and to a combination of both. The reproducibility of the test data is quite satisfactory.

3. To achieve high prediction accuracy, the radiation property of all model surfaces, participating in radiant exchange with the surrounding or among themselves, must be held within close limits identical to that of the corresponding surfaces of the prototype. Assuming that the foregoing can be achieved, a model which performs well when heated electrically would perform equally well when heated by beam radiation. However, the effect of inaccuracies in beam intensity, beam divergence, spectral variation, unsteadiness, etc., has not been investigated.

4. Like the use of model testing in fluid flow and structural dynamics, the quality of data is, to some extent, dependent on the experience and skill of the experimenter. The proper installation of thermocouples or other temperature sensors is of prime importance.

In recent years, adhesive metal foil tapes (e.g. the copper and aluminum tapes manufactured by Mystik Tape, Inc., of Northfield, Illinois) became commercially available. It is conceivable that they can be more conveniently and advantageously employed for controlling the material effective conductance than by electroplating. One also sees, quite obviously, the possibility of controlling the effective heat capacitance by using plastic tapes. However, the range of thickness of such commercially available tapes is limited. Thus, the desired thermal conductance and capacitance of the various structural members of the system may not be precisely manufactured. Furthermore, the application of a metal foil tape to a surface would at the same time introduce a minor disturbance to its heat capacity. Likewise, the addition of a plastic tape would produce some disturbance on its conductance. The recognition of these facts again points to the desirability of developing a technique of modeling in which models that do not completely conform to the similarity criteria can be used.

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1. Vickers, J. M. F., "Thermal Scale Modeling," Astronautics and Aeronautics, V. 3, No. 5, p. 34 (1965).

2. Jones B. P., "Theory of Thermal Similitude with Applications to Spacecraft--A Survey," Astronautica, V. 12, No. 4, p. 258 (1966).

3. Chao, B. T. and Wedekind, G. L., "Similarity Criteria for Thermal Modeling of Spacecraft," Journal of Spacecraft and Rockets, V. 2, No. 2, p. 146 (1965).